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SIXTEENTH ANNUAL MEETING
APRIL 25 AND 26, 1935
WASHINGTON, D. C.

PART I
REPORTS AND PAPERS, GENERAL ASSEMBLY
AND
SECTIONS OF GEODESY, SEISMOLOGY, METEOROLOGY, TERRESTRIAL MAGNETISM AND ELECTRICITY, OCEANOGRAPHY, AND VOLCANOLOGY

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INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now seven sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, and (g) Hydrology. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section; the Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology.

Annual assemblies of the Union and annual meetings of its sections for the discussion of reports and for symposia are held each year. The first thirteen assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C.; in 1933 and 1934, in addition to the annual general assemblies and meetings of each of the seven sections held in Washington, D. C., meetings of the Section of Hydrology were held at Berkeley, California. The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 56; eighth, 1927, Bulletin No. 61; and ninth, 1929, Bulletin No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, fourteenth, and fifteenth annual meetings were published in June 1931, June 1932, June 1933, and June 1934, respectively, in the series of miscellaneous publications of the National Research Council. The present volume, also one of the miscellaneous publications of the Council, includes the transactions of the sixteenth annual meetings held at Washington April 25 and 26, 1935. At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The papers presented at the General Assembly were devoted to a symposium on the Earth's outer atmosphere. These concerned recent developments in atmospheric absorption of light and its relation to ozone, in atmospheric ionization, in the correlation of radio transmission with solar phenomena, in the theory of the ionosphere, in the conditions resulting from the study of meteor-trains, in the contribution to atmospheric ionization by cosmic radiation, in the relation of ultra-violet solar radiation and ozone, and in the relations of the aurorae and night-sky spectra to the upper atmosphere. Five reports were presented from special committees relating to geophysical and geological studies of oceanic basins (with five appendices developed from the Committee's work) and of continents. As a matter of record, a complete statement regarding the cosmic-data Ursigrams and codes used was added in the transactions. Among the 16 resolutions adopted were: Three relating to suitable vessels for magnetic and oceanic surveys and for bathymetric charts; three relating to data in geophysics, geology, and hydrology obtained by the Federal Government and to the coordination of the results; one recommending the publication of a manual of hydrology; three on the establishment of mountain stations, on the use and design of radio meteorographs, and on the coordination of snow-surveys in mountain regions; and three on the establishment of additional seismograph-stations in the United States.

In the Section of Geodesy eight papers and reports dealt with time-service present and future developments, surveys in Canada and Mexico, mapping of the United States, international standardization of base-line tapes and wires, absolute gravity at Washington, and progress of geodesy in the United States.

The Section of Seismology devoted particular attention to deep- and shallow-focus earthquakes in three papers, to subsurface exploration by earth-resistivity and seismic methods in one paper, to instrumental designs and studies in three papers, to propagation of waves in two papers, to motion of a viscous fluid under surface load in one paper, and to a progress-report of cooperative seismological research during the year.

The rapid development and improvement in meteorological research in the United States was evidenced by the 13 papers before the Section of Meteorology. Among the subjects discussed were: Use of cloud-observations in forecasting snow-storms; methods of physical weather-analysis; hurricane-warning service and its reorganization; cyclone-frequency in the tropics and distribution and frequency of tornadoes in the United States; meteorological periods; theoretical study of wind-velocity and wind-direction; upper-air research involving use of ultra-high frequencies in tracking meteorological balloons, of the radio meteorograph, and of the airplane; observations on mountain peaks; and auroral observations at the International Polar Year station Point Barrow.

In the Section of Terrestrial Magnetism and Electricity, one paper dealt with the correlation of auroral and magnetic activities at Little America as observed by the second Byrd Antarctic

Expedition; two with earth-current results particularly during International Polar Year; two with application of, and instrumentation for, magnetic methods in determining subsurface geological features; and one each with earth-magnetic analysis of primary cosmic radiation, theory of rain and thunderstorms, relation of ozone-measurements and solar cycle, purpose of further atmospheric-electric measurements in the troposphere and stratosphere, and the need for more detailed magnetic observations shown by the increasing application of results. Progress-reports on magnetic and electric work were received from nine governmental and private organizations in North America including Canada, Mexico, and the United States.

The Section of Oceanography heard six progress-reports on oceanographic research accomplished in Canada and the United States. Six papers dealt with the continental margin on George's Bank, seasonal temperature-variation in the North Atlantic, the natural regions of the world ocean according to Schott, California submarine canyons, hydrographic relations between the Gulf Stream and the Gulf of Mexico, and submarine daylight; and one paper dealt with the design, construction, and use of a marine coring-instrument.

Three meetings of the Section of Volcanology were devoted to the presentation and discussion of 11 papers bearing on rock-types and vulcanism of southeastern and interior Alaska, of the southern Appalachians, of California, of Colorado, of southeastern Idaho, of central Montana, of New Mexico, of Nevada, of eastern Pennsylvania and Maryland, of Wyoming, and of Ontario. One paper treated of the equilibrium-relations between feldspathoids, alkali-feldspars, and silica. One paper reported on the vestige of a Pleistocene thermal activity in Iceland.

As in the transactions of 1934, the annual reports submitted to the Section of Hydrology from its nine permanent research committees comprise significant digests of progress and development in investigations on snow, glaciers, evaporation, absorption and transpiration (including extended list of terms and definitions), rainfall and runoff (with five appendices of experimental studies and results), soil-moisture, underground water (with two appendices on the relations with oil fields and on active projects in California, Oregon, and Washington), dynamics of streams, and chemistry of natural waters. Nineteen papers and reports cover many diverse fields of hydrological research, both experimental and theoretical; they serve to emphasize the widespread activity in hydrology in the United States and the need for further support by State and Government in this field. Three meetings of the Section were held.

The General Secretary edited the manuscripts for publication after some preliminary editing by the secretaries of sections. The cost of publication was met through allotment by the National Research Council for maintenance of the Union, annual dues of members of the Union, and contributions of money and of services from the Harvard University, from the Carnegie Institution of Washington, and from members of the Union. C. C. Ennis proof-read the typed copy, and the authors, except for a few who could not be reached, also revised their matter as prepared for publication. The final copy was prepared by J. J. Capello, whose skill and constructive arrangement of the copy are evidenced in the excellent reproduction by the A. L. Sauls Planograph Company of Washington. Besides its obligation to authors, to members of committees, and to our colleagues in Canada, Mexico, and abroad, who contributed to the Sixteenth Annual Meeting, the Union is indebted to W. C. Hendrix for preparing many drawings of which the originals submitted were not suited for planographic reproduction and to J. W. Green and P. G. Ledig for photographic work.

The many requests being received from geophysicists in all parts of the world indicate the value of the Transactions in disseminating the results and progress of work done in America and in forwarding that international interchange of research so essential to the science of geophysics and its steadily growing interpretation, utilization, and application.

J. A. Fleming, General Secretary
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

Sixteenth Annual Meeting

GENERAL ASSEMBLY

Washington, D. C.
April 26, 1935

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REPORTS OF COMMITTEES

REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF OCEANIC BASINS

R. M. Field, Chairman

D. C. Barton	J. A. Fleming	A. Keith	F. P. Shepard
W. Bowie	N. H. Heck	G. W. Littlehales	W. P. Woodring
W. H. Bucher	C. A. Heiland	J. B. Macelwane	P. Weaver
E. L. De Golyer	D. W. Johnson	H. A. Marmer	F. E. Wright

As stated in its first report to the fourteenth annual meeting in 1933, the Committee has attempted to promote:

(1) The application of geophysical methods to the study of oceanic basins and submerged continental margins, including the modification, perfection, and invention of new apparatus and techniques.
(2) The discussion and organization of such oceanographic projects as appear to be of particular importance to the advancement of geodesy and geology.

It is expected that there will be complete cooperation between this Committee and the recently organized Committee on Geophysical and Geological Study of Continents, and it is to be noted that there are a number of reasons why this cooperation should develop naturally and rapidly, including:

(1) The natural desire on the part of geodesists and geologists to make the greatest possible use of geophysicists and geophysical methods.
(2) The common desire to procure fundamental geological data concerning the drowned continental margins, especially of North America, where they form the seaward extension of the great structural features commonly referred to as "geosynclines."
(3) The necessity of comparing the composition and structure of the rocks which underlie the oceanic basins and continents.
(4) The geological importance of the study of the major island-arcs, including the fore-deeps.
(5) The comparative study of contemporaneous and ancient marine sediments.

During the past year the Chairman has discussed the above problems with all the members of the Committee, either verbally or by letter. He has also participated in conferences on the organization of three expeditions:

(1) The project for a seismic study of the Atlantic continental shelf is under the direction of Professor Benjamin L. Miller and Dr. Maurice Ewing, both of Lehigh University. The plans have been carefully matured with the valuable advice of Captain R. S. Patton, Captain N. H. Heck, Rev. J. B. Macelwane, S.J., Frederick W. Lee, Commander G. T. Rude, and Major William Bowie. Dr. Ewing will be in charge of the seismic determinations on the coastal shelf and at sea, with the aid of a grant from the Geological Society of America and the cooperation of the vessels of the United States Coast and Geodetic Survey.
(2) At the suggestion, and with the advice, of Professor Francis P. Shepard, Dr. H. C. Stetson, Professor E. G. Conklin, and Professor Douglas W. Johnson, a project is now being discussed for detailed submarine mapping of the North Atlantic. The Committee has naturally sought the advice of numerous experts and cooperative agencies, and feels that an excellent summary of the present status of the problem has been presented by Captain Patton, and submitted as Appendix B of this report. It seems necessary, however, to include one paragraph from Captain Patton's communication in the body of our report: "It would not be worth while to attempt the production of a new bathymetric chart on the basis of the data now available. Only if we can secure additional data does the project become worth while." However, a submarine relief-map of the continental border of the whole west coast of the United States should be published as soon as possible because the necessary data will be completed this fall.
(3) Plans are still being discussed for another gravity-survey in the Gulf-Caribbean region, and also along the line of the seismic traverse described under project 2. Dr. Donald C. Barton has suggested: (a) The attempt to determine a Gulf Coast geosyncline; (b) the southward extension of the Appalachians under the overlap of the Gulf Coastal Plain; (c) the relation between the salt-basin and the edge of the continental shelf in the Mississippi Delta area, in which the salt-domes are known to extend practically to the edge of the continental shelf.

If a series of gravity-profiles were run off the Texas-Louisiana coast, they would undoubtedly yield important data on the above problems, especially if they were supplemented by two pro-

files determined by the United States Coast and Geodetic Survey southwest of their former two profiles across the southern end of the Appalachians.

The Committee is in complete agreement that the easterly extension of the negative anomalies in the West Indies should be traced as soon as possible. In this connection the Chairman has continued his conversations with Dr. Bigelow and the Norwegian authorities who are at present the custodians of the Meinesz apparatus, originally owned by the Woods Hole Oceanographic Institution. Professor H. U. Sverdrup has informed the Chairman that a French expedition has a previous bid for the use of the apparatus in the Mediterranean in 1936. Conversations with officers of the United States Navy are now leading to a tentative proposal for a marine gravity-expedition in the West Indies in the winter of 1935.

Aside from the projects mentioned above, the Chairman has been advised to condense the opinions and suggestions of the Committee under the following headings.

(I) Sounding and submarine physiography--The rapid advance which has been made in the perfection and ease of sounding, and more particularly the greater accuracy in positioning, during the last five years, leads naturally to the following conclusions:

(1) Recent developments in the methods of deep-sea hydrography make possible an improvement in the quality and quantity of that work fully comparable to the better results attainable by the modern methods of topographic surveying as compared with those available half a century ago.
(2) Owing to the inaccuracy of many of the existing soundings, especially when charted on astronomical determinations, where the recent methods have been applied they have practically rendered obsolete the bulk of the existing sounding-data, in much the same sense that the recent topographic maps of the Federal Geological Survey have rendered obsolete the earlier reconnaissance maps of that bureau.

The Committee considers that a full appreciation of the modern practice in sounding and positioning at sea is so important that it quotes in full an account of "The accuracy of soundings and positions obtained by methods used in the United States Coast and Geodetic Survey" as appendix A of this report.

In regard to the physiographic problems of the submerged continental shelf, the discovery and study of submarine canyons continues to be of paramount importance. Both Professor Shepard and Dr. Stetson have reported on this subject in the Section of Oceanography, but it is necessary also to mention other problems, such as:

(1) Determine if the mouths of the submarine canyons on the Pacific and Atlantic margins are at the same depths.
(2) Attempt to determine the age of the canyons by dredging rock-specimens from the walls and by taking cores in the center of the valleys.
(3) Intensive mapping of apparent east-west "Valley-and-ridge" submarine structures in the middle, north Atlantic, on a line between Newfoundland and Cornwall.
(4) The possible recognition of the "glacial shore-line," assuming that the strand-line occurred some 300 feet lower during the glacial period than it does at the present time. A specific example of the application of a sounding survey to the possible solution of such a geological problem is given in appendix C by Professor Paul MacClintock.

(II) Gravity--Gravity is, thanks to the unique ability and stamina of Dr. F. Vening Meinesz, the leading technique for studying the character of the rocks which underlie the oceanic basins. Dr. Meinesz is now engaged on one of his most extensive expeditions for the determination of gravity at sea. He left Helder (Holland) November 14, 1934, and after working in the Atlantic and Indian oceans is expected to reach Soerabaya (Dutch East Indies) July 11, 1935. The following is a quotation from a letter to Major Bowie written on January 21, 1935, from Pernambuco:

"We are diving twice or thrice a day and in this way we made 32 stations between Dakar and Pernambuco, bringing the total up to 94 stations. The most interesting stations of this last crossing are those over the Romanchi Deep (7600 meters between two ridges of 2600 and 3400 meters depth)." It is of great interest to oceanographers that Dr. Meinesz is crossing the South Atlantic with two lines of gravity-stations. The oceanographic expedition of the Meteor, a German ship, several years ago found that the configuration of the bottom of the South Atlantic is very irregular in places. It is assumed that Dr. Meinesz is following routes across the South Atlantic that will take advantage of the information disclosed by the Meteor. (Bowie)

Recently the question has been raised as to whether or not some machine for measuring gravity

other than the Meinesz apparatus might be used for determining gravity at sea, especially on the deck of a surface-vessel. It is the opinion of the Committee as summed up by C. H. Swick that "The Meinesz apparatus is the only one so far developed that will give the requisite accuracy to meet scientific requirements." Mention should perhaps be made of an "Improved apparatus for taking gravity-measurements at sea on board an ordinary vessel" as described by a Japanese investigator Chuji Tsuboi in the Proceedings of the Imperial Academy (v. 10, No. 10, 1934). The accuracy of this instrument is apparently still open to question, and the inventor makes the following statement: "Although the results obtained were as a whole satisfactory and fulfilled expectations, I found that several improvements should be made on the apparatus to get still better results. Accordingly an improved apparatus has been newly constructed .... and the apparatus being now completed will be taken to voyage in the nearest future and the results of the gravimetric measurements will promptly be reported." Dr. C. A. Heiland has also informed the Chairman that "a gravity-measuring instrument, usable on board ship, is now being developed by a commercial organization with which I am connected. This machine at present gives an accuracy for ship-observations of about 10 milligals to 1 milligal. This machine will be available in 1936 at which time it is offered to your Committee for trial."

As stated in a previous report, the Committee has suggested the desirability of simplifying the method of applying a correction at each gravity-station for the difference in elevation between the actual geoid and the mathematical spheroid on which the gravity-formula is based. Special tables have been computed by the United States Coast and Geodetic Survey for this purpose and are now available, as reported by Mr. Swick in appendix D.

In concluding this necessarily abridged report on gravity at sea, the Committee heartily recommends that every possible effort should be made to support Dr. Meinesz in his splendid pioneer work, and to promote comparative geophysical and geological studies in the East and West Indies. A continuation of the easterly pursuit of the important line of negative anomalies in the West Indies is highly essential, as well as a further prosecution of the surface structural geology in this region. We are happy to report that a second gravity-survey of Cuba, sponsored by the Committee, and accomplished with the cooperation of the Cuban Government, the United States Coast and Geodetic Survey, and the Atlantic Refining Company, has been successfully carried on during the past winter, under the enthusiastic and most able supervision of Dr. R. E. Dickerson. About 75 determinations have been made. One anomaly has been reported of +116 milligals which is larger than any ever found in the United States, in spite of the fact that the station is only about 20 miles from one with a negative anomaly.

Dr. W. P. Woodring admirably sums up the structural problems of the West Indian geology as follows: "The limits and possible significance of the strip of negative anomalies north of Haiti and Puerto Rico are matters of considerable interest. So far as the last period of deformation (Miocene-Pliocene) is concerned, this strip extends along structurally dissimilar parts of the West Indies and fails to continue along structurally similar parts--features in which it differs from the East Indian strip. The Tertiary rocks of Cuba and Haiti are deformed, whereas those of Puerto Rico are tilted or gently flexed. Perhaps the West Indian strip bears some relation to an earlier period of deformation (late Cretaceous), but in that event it would be expected to continue westward north of Cuba, or possibly along the outer edge of the Bahamas. This conception also implies a long lag in isostatic adjustment in terms of the significance of the East Indian strip, as set forth by Dr. Meinesz. So far as known, there does not appear to be evidence of northward thrusting toward the strip in Haiti or Puerto Rico in either period of deformation, but perhaps the data have not been systematically gathered. An effort should be made to analyze the data, and to obtain data where they are lacking. The lack of detailed information on the geology of large parts of Cuba handicaps any investigation dealing with West Indian geology. The character of Tertiary deformation in the Lesser Antilles is not clearly known. If the foundation of the arc of the Lesser Antilles consists of Cretaceous folds, they are inaccessible.

"The relation between the trends of Cretaceous and Miocene folds needs further investigation. At many places--at least in Jamaica, Haiti, and Puerto Rico--the Miocene folds or the strike of Tertiary beds where there are no folds, extend obliquely across the earlier folds. The dating of the Bartlett Trough and other submarine features depends primarily on the relation of these trends."

(III) Seismic--The discussion of seismic methods as applied to geophysical and geological study of oceanic basins and their margins may be subdivided under the headings of natural earthquakes and artificially generated earth-tremors. The project for the application of the latter method to the study of the submerged continental margins has already been discussed under project 1. It remains to call attention to the need for a more careful comparison of the rates of transmission of seismic waves through the continents and ocean-basins. Captain Heck reminds us of the

fact that "The question is raised by B. Gutenberg in his Grundlagen der Erdbebenkunde (see page 165 and illustration 75). He draws the conclusion that the thickness of the granitic layer under Eruope is 60 km, under the Atlantic is 30 km, and under the Pacific is zero. Extensive studies of Samoa records by Angenheister and of Honolulu records by Neumann show that the velocity of surface-waves beneath the Pacific is 18 to 20 per cent greater than beneath the continents. Lest and Neumann conclude that the same high-speed wave is common in both the Atlantic and the Pacific records, but that it has much less energy in the Atlantic. The conditions for further study of this problem by means of records from stations in the eastern United States are seen to be excellent. It is obvious that the greater earthquakes are far more important for such a study and it is readily seen how many more will have an all-ocean path except at their end to the United States than to Europe. Africa shuts off most of the active equatorial area and deductions from a part-ocean path, part continental path, are not very conclusive. It is probable that there are now numerous records available for this study, and there will be a steady accumulation as time goes on at the twelve seismograph stations in the eastern United States and Puerto Rico. It would be very desirable to have a new study made of this problem." In connection with this problem, Captain Heck has conferred with Professor Conklin regarding the importance of the installation for suitable seismographs at Bermuda. Professor Conklin is now in correspondence with his colleagues of the Bermuda Marine Biological Laboratory, as well as with the Colonial and British Government officials regarding this matter, and there is every expectation that a suitable seismograph will eventually be operated at Bermuda.

(IV) Marine sedimentation--The Committee believes that the seismic submarine survey as planned under project 1 of this report will yield information as to the (1) depth of the veneer of sediments on the coastal shelf, (2) the extent to which the coastal shelf is being extended by the accumulation of detrital sediments, and (3) the amount of sediments on the floors of the submarine "river-valleys."

It should be noted that all of the surveys discussed in this report will also afford the opportunity for the collection of bottom-samples, but the Committee is naturally interested in the development of any device which will produce at least more than a few vertical inches of the bottom deposits. At the present time, Dr. C. S. Piggot of the Geophysical Laboratory of the Carnegie Institution of Washington appears to be the only one who is conducting successful experiments along this line with the cooperation of the Geological Society of America. Dr. Piggot informs us that "The problem has resolved itself into one of ballistics and mechanics and the first, multiple-explosion-type apparatus, while functioning mechanically, served only to point the way toward a single-explosion type which we are hopeful will prove much more successful. The second apparatus is expected to leave the ship tomorrow (March 5, 1935). It will be shipped to the military powder research laboratory of the E. I. du Pont Company, where it will undergo tests and firing to discover the most advantageous type of powder and energy of discharge, and then will be brought back for such alterations as may be found necessary. We are quite sanguine of the new apparatus and if our expectations materialize I should have some short cores by April 25. I should be very glad to exhibit them and the machine and to discuss its operation, but I feel that the uncertainty involved makes it unwise to put me on the program in advance."

In concluding his report the Chairman wishes to express his great indebtedness to the members of the Committee as well as all those who have spent so much time and labor in discussing the present and future possibilities of the application of geophysical methods to the geological study of oceanic basins and their margins.

Princeton University,
Princeton, New Jersey

APPENDIX A--THE ACCURACY OF SOUNDINGS AND POSITIONS OBTAINED BY METHODS USED IN THE UNITED STATES COAST AND GEODETIC SURVEY

Paul A. Smith

With the advent of acoustic methods in navigation and in hydrographic surveying, the field of accurate hydrographic surveying has been extended to several hundred miles off the coast, and many details of the ocean-bottom now can be obtained and charted with far greater fidelity than was possible in the past. The discovery of submarine valleys at the edges of the continental shelves, and the development of the details and configuration of the ocean-bottom in greater depths as aids to navigation, are opening up a wealth of information for the use of geologists and oceanographers. This paper has been prepared in answer to repeated inquiries as to the accuracy of soundings, that is, the probable errors of soundings both in depth and in position. In order that the soundings of various hydrographic surveys may be interpreted with complete

understanding of their weights, some knowledge of the methods used in making such surveys is desirable. A brief description of the various methods is given for that purpose.

It should be remembered that the first purpose of the hydrographic surveys made by the United States Coast and Geodetic Survey is to obtain the necessary information for constructing a nautical chart, and that the least depths over shoals are of more importance to navigation than the deepest depths in valleys. Long ago, charts were adequate if they showed only the shore-line, important shoals which were dangerous to navigation, and the main passable channels, with a few additional soundings to give the navigator a rough idea of the depths. With increased speed of ships, the need for more and more details of the ocean-bottom has grown until now, with modern high-speed vessels equipped with echo-sounding devices, it would appear that a good contour map is desirable to satisfy all the needs of modern navigation. A sudden change, however, from the present practice of charting to one that shows only the depth-curves with soundings given only for the least depths and the depths of the valleys or depressions, would not be accepted readily by the majority of seagoing people, for seafaring is one of the most conservative professions. As the need grows, charts may be altered, but for the present geologists may use the field-sheets which usually are constructed on a larger scale than that of the printed charts, and which provide more complete data for the drawing of contours and depth-curves. In any case, the drawing of contours from soundings should be done only with a full knowledge of the accuracy to be expected in depth-measurements, and the associated positions. The usual controversy between the cartographer and the geologist relative to the interpretation of the various depth-curves hinges upon the fundamental difference between a nautical chart and a geological map. The charting agency is charged with charting the waters for the purpose of publishing navigational charts to serve the merchant marine and the Navy. It should be realized that, unless undisputed evidence that a certain depth-curve occupies a certain position is obtained, the cartographer hesitates to show the curve. Where soundings are not adequate to completely prove the form, the geologist usually interprets the shapes from his experience and knowledge of various geological forms, but the cartographer maintains that too much imagination is used in such delineation by geological interpretation. For these reasons it has been the policy of the Coast and Geodetic Survey to show on its charts only such depth-curves as can be determined with certainty. This applies to the detailed surveys made in shoal waters. The general form of the 100-fathom curve and in some cases that of the 1000-fathom curve have been shown on small-scale charts.

Inshore-soundings, that is, surveys within sight of land, usually are controlled by observations taken from the surveying vessel by means of sextants, sighting objects on shore which have been located by triangulation, or topography. This type of control is used on the Atlantic and Gulf coasts to about 15 miles offshore, approximately the limiting distance for visual fixes from triangulation-signals, water-towers, high buildings, or other structures that provide visible objects up to that distance. On the Pacific Coast, the coasts of Alaska, the Hawaiian Islands, the Philippine Islands, Puerto Rico, and, in general, on all coasts where mountain peaks and other objects are sufficiently high, the visual control can be carried by the surveying vessel as far offshore as these can be seen, weather-conditions and visibility being the most important restrictions. A sketch of the usual plan followed in development of a hydrographic survey by visual control is shown in Figure 1. The sounding vessel proceeds along courses so determined as to give the most economical development of the area, but in general for the preliminary survey these courses are set so that the direction of the sounding-lines are approximately normal to the trend of the contours. Any indications of shoaling or of channels are noted and subsequently investigated by the hydrographer by splitting the first system of lines until he is satisfied that he has obtained the least depth over questionable areas. In some cases, where pinnacle-rocks and irregular formations reach close to the surface, the wire-drag is used to insure that the areas are clear for navigation.

Beyond the limits of visual control, and in regions where foggy weather prevails, radio acoustic ranging has been used with remarkable success by the Coast and Geodetic Survey for the past ten years. This method, combined with echo-sounding, has greatly reduced the unit costs of all hydrography, and in addition has given more complete data. Figure 2 and Figure 3 show the fundamental principles and the procedure followed in radio acoustic ranging. The position of the ship is fixed by its distances from the hydrophones of two suitably located shore-stations, the distances being determined by the time required for sound to travel underwater from the ship to each station. At each station a hydrophone is anchored a short distance offshore, and a few feet from the bottom, in comparatively shoal depths, seldom exceeding 10 fathoms. The hydrophones are located in position by sextant-angles from shore-points, and are connected by cable to automatic amplifiers and radio transmitters in the temporary shore-stations. On board ship a hydrophone within the hull and a radio receiving set are connected electrically with a chronograph so that the time of arrival of underwater sound-waves or of radio signals is recorded on the chronograph-tape. To obtain a position, a small bomb, so timed as to explode when it reaches a

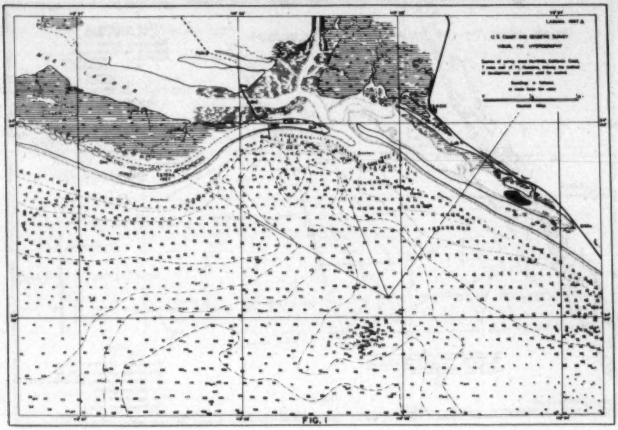


FIG. 1

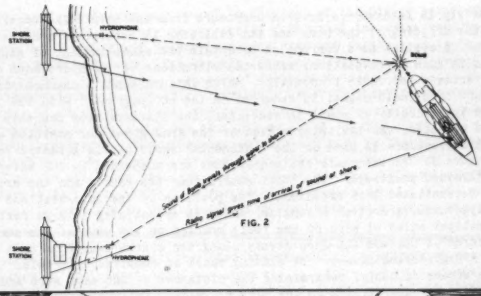


FIG. 2

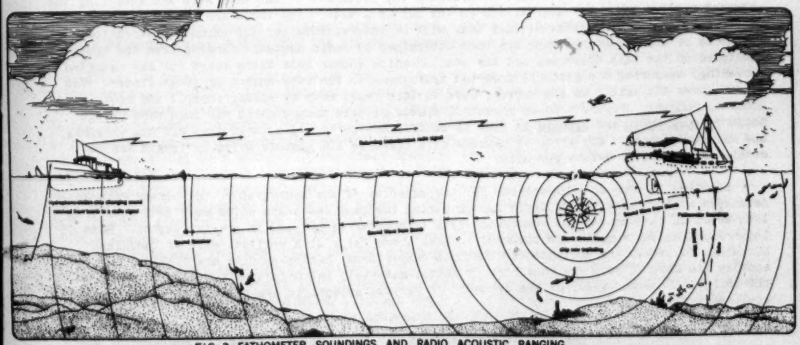


FIG. 3- FATHOMETER SOUNDINGS AND RADIO ACOUSTIC RANGING

Showing two of the scientific methods employed by the Coast and Geodetic Survey of the Department of Commerce to insure an unsalled chart: (1) correct water depths and (2) the precise positions of such depths, many of which are given for water areas far out of sight of land. Depths are determined with a fathometer, which measures the time required for a sound to travel to the sea bottom and return to the ship as an echo. They are made at the rate of 6 per second, while the survey ship proceeds back and forth over the area at her regular speed. The positions of these depths are fixed by radio acoustic ranging, from two previously determined positions, such as two station ships (of which one is shown). The time elapsed between the sound from the bomb as sounded on the survey vessel, and the radio wave from the station ships, is measured on the surveying ship to one one-hundredth of a second. Knowing the velocity of sound in water, the distance between the survey ship and each of the two station ships can be calculated accurately, even when separated by as much as 100 miles.

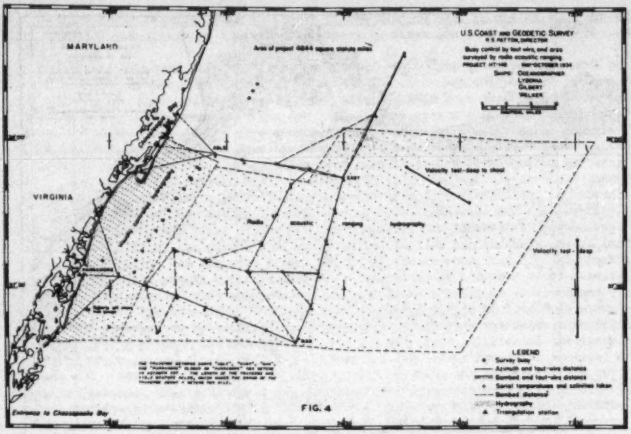


FIG. 4

depth of approximately 15 fathoms, is dropped overboard from the ship while underway. The time-interval between the dropping of the bomb and its explosion is determined and the ship's run in this short interval is applied as a correction to obtain the exact instant of explosion. The sound also travels to each shore-station, where the vibrations of the hydrophone cause an electrical impulse to actuate the radio transmitter, which in turn sends a characteristic radio signal to the ship, and this radio signal is recorded on the chronograph. With the time-interval thus obtained, and the velocity of sound in sea-water, the distance from the ship to each of the hydrophones can be computed, and the intersection of the arcs gives the position of the ship. A modification of this procedure is used on the continental shelf of the Atlantic and Gulf coasts, and is shown in Figure 3. In this case the hydrophones are suspended in the water from ships anchored on predetermined positions. The shoal waters near the coasts and the extent of the continental shelf necessitated this expedient. The position of the ship-stations is determined by the taut wire-apparatus, a British invention, which is essentially a large reel of steel piano-wire (140 nautical miles of wire on one reel) mounted on the deck of the surveying vessel. With the wire anchored at one end the ship steams along her course away from this anchor and pays out the wire over a registering sheave. By placing buoys at required intervals, the ship runs a traverse along the scheme of buoys, determining the distances by the taut wire and measuring the azimuths between buoys by observations on the Sun or a star. The buoys are placed at intervals of about seven to eight miles so that they will be intervisible for the azimuth-observations. Positions of supplementary buoys are then determined by radio acoustic ranging from the buoys established on the main traverse, and the station-ships anchor near these buoys for the detailed surveying, measuring the distance from the hydrophone to the buoy-anchor by range-finder. The figure shows the extent of the surveys made in this case, both by visual control and radio acoustic ranging. Figure 4 shows a control scheme of this nature which was laid down by the ships Oceanographer and Lydonia in 1934 to control the survey of a large area off the Virginia and Maryland coasts. The error of closure of a traverse 115 statute miles in length was 464 meters or about four meters per mile.

Sounding is done by echo-methods for the majority of the hydrography, the Dorsey Fathometer developed by the Coast and Geodetic Survey during the past two years being used in depths less than about 15 fathoms and the commercial-type fathometer being used in greater depths. Both of these sounding instruments are compared several times daily with vertical-wire or hand-lead soundings to verify the indications. On such comparisons, bottom-samples are obtained and these samples are used to note the character of bottom-material, which information also is shown on the charts. In some cases, at the requests of various scientific organizations, these samples are preserved.

The method of recording fathometer-soundings, as has been used since the adoption of echo-sounding in the Survey is to observe the indications of the fathometer, recording the depths at frequent intervals--one minute, 30 seconds, or less--depending upon the depths. Although the

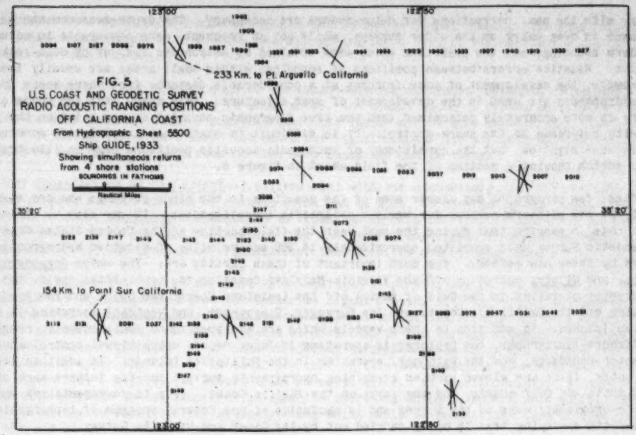


FIG. 5
U.S. COAST AND GEODETIC SURVEY
RADIO ACOUSTIC RANGING POSITIONS
OFF CALIFORNIA COAST
From Hydrographic Sheet 5800
Ship GUIDE, 1933
Showing simultaneous returns
from 4 shore stations
SOUNDINGS IN FATHOMS
Nautical Miles

fathometer gives twenty soundings per second in the case of the Dorsey Fathometer and four soundings per second in the case of the commercial fathometer in depths less then about 100 fathoms and about one sounding per second in depths over 100 fathoms, it is obviously impracticable to record so many soundings. The graphic recorder developed by a commercial firm is used on one surveying ship of the Bureau. Because it is an additional instrument which must be verified by visual observation, and for which corrections must be made, it has not been used as a permanent record. In addition to this, the records obtained by the graphic recorder require more work for reduction to the soundings that are selected for the chart than is at present necessary with visual recording. The soundings which are placed on the field-sheets, therefore, represent soundings that are observed, or are read from the fathometer-dial at various intervals, and might not in all cases show the small changes in depth between soundings. Ordinarily, the observer makes a particular effort to record any change in depth and the exact time at which the change occurs, in addition to the regular soundings that are taken at specified intervals.

From experience with comparisons over several years and from a consideration of the various instrumental difficulties, it is believed that the soundings, depending on the character of the bottom and the type of instrument used, are accurate to within one-half of one per cent up to 10 fathoms, within about one per cent between 10 and 200 fathoms, and within about three per cent over 200 fathoms. In some of the first echo-sounding, these limits were exceeded, but recent work is believed to be well within the stated percentages.

Errors in location of positions by visual fix as of any given survey are usually correct to within one part in 500 to 1000, depending upon the relative positions of the control-stations and the distances offshore. For radio acoustic ranging-positions the accuracy is about one part in 200 to 500, again depending upon the locality surveyed and the positions of the shore-stations. As an instance of the agreement between several distances determined by radio acoustic ranging in practice, a copy of a section of the field-sheet of the ship Guide, Coast of California, is shown in Figure 5. In this case there were four shore-stations in operation which gave returns to the ship from four separate locations. The actual discrepancy in the distances as determined from the various hydrophone-locations is shown by the short sections of the intersecting arcs. The distances from two of these shore-stations are noted at two of the positions. From a study of this Figure, it will be obvious that there are no very large discrepancies; the experiments which have been made in recent years between known points indicate that the methods are quite dependable. It is most desirable as contrasted with the only other practical method of determining position, namely, astronomic fix. Ordinary astronomic positions taken from vessels underway are hardly dependable within one mile, although where it is possible to anchor for a series of astronomic sights it has been possible to determine the position within about one-quarter of a mile.

Some of the older surveys were based on a datum no longer in use. In correlating these old

surveys with the new, corrections for datum-change are necessary. The depth-measurements which were made in deep water on the older surveys, while not so frequent, were comparable in accuracy to modern sounding; but the positions which were obtained by astronomic fix, or by dead-reckoning, were not. Relative errors between positions of soundings within small areas are usually less; for example, the development of some features at a considerable distance from shore where the same hydrophones are used in the development of such a feature. This means that the shape of the feature is more accurately determined than the true geographic position of any point on the feature with reference to the shore-control. It is difficult to state what the relative accuracy in this case might be, but the consistency of such radio acoustic positions also is illustrated in the sketch showing a section of the field-sheet in Figure 5.

These few paragraphs may answer some of the questions in the minds of those who are making use of the new offshore-surveys for various scientific investigations. It may also be of interest to note in passing that during the past year the field-parties of the United States Coast and Geodetic Survey have completed approximately 14,900 square miles of detailed hydrographic surveys by these new methods. The most important of these parties are: The ships Oceanographer, Lydonia, and Gilbert operating off the Virginia-Maryland Coast on the continental shelf; the Hydrographer operating in the Gulf of Mexico off the Louisiana Coast; the Guide and the Pioneer operating off the California Coast; and the Surveyor, Discoverer, and Westdahl operating in the Aleutian Islands. In addition to these vessels which are equipped to do radio acoustic ranging for offshore-hydrography, the Explorer is operating in Puget Sound, using visual control and fathometer-soundings, and the Fathomer, operating in the Philippine Islands. In addition to these ships, there are eleven parties conducting hydrographic surveys for the inshore-work on the Atlantic and Gulf coasts, and one party on the Pacific Coast. This is representative only of the hydrographic work of the Survey and is exclusive of the Federal program of topographic and geodetic surveying that is being carried out by the Coast and Geodetic Survey.

U. S. Coast and Geodetic Survey,
Washington, D. C.

APPENDIX B--PROPOSAL FOR A BATHYMETRIC CHART OF THE NORTH ATLANTIC OCEAN

R. S. Patton

The value of a better chart of this character than now exists is so well established that for the present purpose no argument regarding the desirability of the project need be advanced. Perhaps, however, the project needs to be defined. I conceive it to be the first pioneering step in an effort to secure a more accurate and more detailed knowledge of the configuration of the ocean-basins. The accumulation of that knowledge will be a long and difficult process. We will never have it in adequate form until the maritime nations of the world have executed special surveying projects for its collection. It is useless to hope that the nations will undertake such projects at this time; in fact, the time when they will do so cannot now be visioned.

In the meantime, however, there is a possibility that if the proper interests can be aroused we can secure a better approximate knowledge of the ocean-basins than we now possess. An effort to secure such approximate knowledge is justified by the years which we must wait before the systematic surveys will become available. The present project is merely in the nature of a reconnaissance.

It would not be worth while to attempt the production of a new bathymetric chart on the basis of the data now available. Only if we can secure additional data does the project become worth while. It is possible that such data can be secured if we can obtain cooperation from ocean-going ships, both of the Government and the merchant marine. I think we must consider the project in terms of five consecutive steps: (1) The determination of its feasibility; (2) organization of the effort; (3) collection of the data; (4) study and analysis of the data; and (5) publication.

(1) The determination of its feasibility--The only feasible method of obtaining additional data is for ocean-going ships equipped for sonic sounding, in the course of their regular voyages, to take such soundings with frequent accurate determinations of positions, thus securing profiles of the ocean-bottom along the tracks followed.

The first step, therefore, is to ascertain the extent to which ships plying the North Atlantic are equipped to take the necessary soundings and are willing to do so. On the ground of simplicity and convenience it probably would be desirable to limit the project to ships flying the United States flag. This, however, is not essential. This first step may well be conducted

informally. As a first move I have written to the Submarine Signal Company, the only manufacturer of sonic-sounding apparatus in this country, asking for a list of the merchant ships suitably equipped for this purpose.

A disturbing factor is that much of the sonic-sounding apparatus installed on merchant ships is designed for service only in shoal water, and cannot sound in depths materially exceeding 100 fathoms. Recent inquiry suggests that this factor may be more serious than I had at first anticipated, and I have asked the Submarine Signal Company for advice regarding the possibilities of modifying the apparatus so that deep soundings can be taken.

(2) Organization of the effort--I believe that with the sponsorship which can be secured for the project and the showing of results which can be made, we can reasonably expect good cooperation from the steamship companies to an extent which does not involve any material expenditure of money. I believe that cooperation from the Federal Government ships can be taken as a matter of course. The problem of organization, therefore, is one of salesmanship.

Having obtained a list of merchant ships equipped to participate in the project (it is hoped that the list requested from the Submarine Signal Company will include ships equipped with apparatus other than that manufactured by that Company) and having classified those ships on the basis of tracks followed, the matter should be presented to the various steamship companies and their cooperation requested. It is understood that several hundred ships are equipped with sonic-sounding apparatus, and if 10 to 20 per cent of them have suitable apparatus and are willing to cooperate, I believe the effort would be worth while. If such cooperation is assured, we should then approach the various Federal agencies operating ships to secure such additional cooperation as may be possible. It scarcely seems worth while to contact the Federal agencies unless the aid of the merchant marine is assured.

(3) Collection of the data--This will be a simple matter which can be fitted readily into the usual ship's routine. Soundings should be taken continuously at frequent intervals--say, 15 minutes--from land-fall to land-fall. At intervals of perhaps every four hours determinations of the ship's position should be made by astronomic observations, in order that we may have the best possible knowledge of the points at which the soundings are taken. Forms for recording the data should be furnished the ships, and these forms should contain detailed instructions for assuring the highest possible quality of the work. As rapidly as the data are secured they should be turned in for study and analysis.

(4) Study and analysis of the data--This is the most important and difficult part of the project. This is a necessary consequence of the fact that the data furnished will be of only approximate accuracy. In the measurements of depths uncertainties will exist due to the fact that many inadequately trained and experienced operators will be used. There will be a tendency, on the one hand, to be suspicious of and to fail to record abrupt changes in depth which actually exist and are indicated by the apparatus, and, on the other hand, to record strays, indicating fictitious depths.

These tendencies should diminish as the operators gain experience and confidence, and eventually should be minor factors in the picture, so that we can expect any consecutive series of soundings to give reliable indication of the depths along the track followed. Even then, however, there will remain the important problem of coordinating the profiles obtained on different voyages along tracks adjacent to one another. This problem results from the fact that the astronomic determination of the ship's positions is an approximate one. Under favorable conditions we must assume that the ship may have been anywhere within the area of a circle of one-mile radius drawn from the center fixed by the astronomic observation. If the soundings on two adjacent profiles are displaced horizontally in opposite directions in the amounts indicated, careful study and analysis of the data are required to prevent erroneous conclusions regarding the configuration of the bottom.

Therefore, the most important part of the project will be this study of the data by expert physiographers, leading to correct conclusions based upon them. To that end also, the collection of data should not be limited to a single line of soundings along any one track. On the contrary, even in the case of a vessel which endeavors to follow the same track repeatedly in consecutive voyages, half a dozen or more profiles thereon would not be too many, as the repetition would help to iron out the discrepancies.

(5) Publication--This should be deferred until the accumulation of data has been sufficient to justify reasonably trustworthy conclusions regarding the bottom-configuration. I should say that we would be fortunate if the chart can be published within five years after the project is undertaken. This final publication of the chart is the only part of the project requiring any

considerable outlay of funds. Since it does not come into the picture until the last thing after the value of the data have been established, its financing should not involve any difficulty.

U. S. Coast and Geodetic Survey,
Washington, D. C.

APPENDIX C--RESEARCH PROJECT ON CONTINENTAL SHELF

The lagoon-deposits along the New Jersey coast seem to lie on the eroded surface of the Cape May gravel-formation. The erosion seems to have been accomplished by streams while this area was above the sea. The evidence is strong that sea-level was lowered 200 to 300 feet during the climax of the Wisconsin glaciation. The evidence would therefore suggest that terrestrial erosion-features should be found on the ocean-bottom out to a depth of something like 300 feet at which level a shore-line should be present. The stream-topography and the glacial shore-line or lines should have been subdued by wave- and current-action as the sea rose to its present position, but it may well be that enough is left to be detectable in a careful survey plotted on a large enough scale and with a small enough interval.

(1) It is suggested that a detailed contour-map be made of the sea-bottom from the present shore-line of New Jersey outward if practical to where the water is about 300 feet, that is, to the glacial shore-line.

(2) If the glacial shore-line can be recognized by its topography and coarse material, ... is suggested that it be followed parallel with the present shore-line both northward and southward from New Jersey to ascertain whether or not it is horizontal. Such a study would give a very significant datum-plane from which to measure post-glacial levels of the land.

APPENDIX D--NEW GRAVITY-TABLES

C. H. Swick

About two years ago, at the request of the United States Hydrographic Office, work was begun by the Coast and Geodetic Survey on some special tables to take account of the indirect or Bowie effect in the isostatic reduction of gravity-stations. The purpose of the tables was to make it possible to apply a correction at each gravity-station for the difference in elevation between the actual geoid and the mathematical spheroid on which the gravity-formula is based. The neglect of this effect has a tendency to produce systematic errors of opposite sign in the isostatic anomalies for land- and sea-stations.

The tables have now been completed and have been used to compute the indirect effect at about 1000 land- and sea-stations. A fairly large part of the discrepancy between land- and sea-anomalies has been eliminated by the use of this correction. Photographic copies of the tables have been sent to geodetic organizations in other countries and it is anticipated that the isostatic anomalies at many additional stations will be corrected in this manner within a short time. It is understood that Dr. Meinesz plans to compute this correction for all his sea-stations except those in the West Indies for which the Coast and Geodetic Survey has already derived the corrected anomalies.

Plans are now being made by the Coast and Geodetic Survey for the publication of the Bowie tables. The tables are in two forms, one a condensed form similar to the Hayford tables for the direct effect as given in the Survey's Special Publication No. 10 and the other a more comprehensive fundamental form known as the Cassinis form. The latter can be used in making investigations involving various theories of isostasy but the former is applicable chiefly to the Pratt-Hayford theory. The fundamental tables correspond to tables for the direct effect recently computed by Cassinis of Italy which will soon be published by the International Association of Geodesy. The Association would publish the fundamental Bowie tables also but for the fact that a section of the tables from a depth of 15 km to a depth of 80 km has not yet been computed as these depths are not needed for making the isostatic reductions on the Pratt-Hayford basis.

The Coast and Geodetic Survey has already expended a great deal of effort on the tables and for its own use does not need the missing section. It is hoped that some other organization may assume the responsibility for computing this part. It is felt that some organization interested in the Airy method of computing isostasy, for which this section is needed, should be willing to contribute this part of the work.

U. S. Coast and Geodetic Survey,
Washington, D. C.

REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS

W. T. Thom, Jr., Chairman

L. H. Adams	maurice Ewing	Beno Gutenberg	Chester R. Longwell
N. L. Bowen	R. M. Field	N. H. Heck	J. B. Macelwane, S.J.
William Bowie	J. A. Fleming	M. K. Hubbert	L. B. Slichter
R. T. Chamberlin	O. H. Gish	E. S. Larsen	H. R. Wanless
Ernst Cloos	W. R. Gregg	F. W. Lee	

The Special Committee on Geophysical and Geological Study of Continents was established because of the Executive Committee's conviction that the cooperative and "simultaneous application of geophysics and geology in an attack upon the major problems of Earth composition and evolution cannot fail to lead to great advances in Earth science"--a restatement of the conviction of all closely in touch with geophysics that the intimate blending of physics and geology will induce as profound a broadening and advance in Earth science as was wrought in chemistry some two decades ago, when physics and chemistry were blended--to the transformation of both.

The Committee has accepted the responsibility thus given it to aid in this new wedding of the sciences, with a deep appreciation of the opportunity offered, and with a full enthusiasm for the work to be undertaken. The problems to be attacked are of great magnitude and of great importance, and the successful execution of this attack obviously will call not only for close team-work within the American Geophysical Union but also will call for a broad, cordial, and interesting cooperation with other units of the National Research Council, and especially with its Division of Geology and Geography and the component units thereof.

Since the appointment of the Committee in February 1935, one general meeting and numerous group-conferences have been held and many letters have been exchanged in order to develop the Committee's plans and the division of work which the situation seems to render appropriate. A tentative survey of the field and allocation of the work to be done has thus been accomplished.

The Committee's preliminary conclusions are:

(1) That we should seek to visualize in full sweep, and in full detail, the geophysical and geological problems which need to be taken up.
(2) That we should check as to which of these problems naturally fall within the field of the Committee, and which are naturally within the fields of other units of the National Research Council--both in order that all scientific rights and interests may be duly observed and that effective cooperation may be developed.
(3) That we should not only seek to lay out our program of work but also should take all appropriate steps to carry this program forward and should secure support for its advancement.

Furthermore, in carrying forward the thoughts just expressed the Committee has tentatively decided that among the things which are obviously needed for the satisfactory advancement of geophysics and of geophysical studies are:

(a) The completion of a series of geophysical control-nets for the United States. (Such control-nets would be scientifically of great importance, and also of great service to operating geophysical concerns and to oil and mining companies interested in an accurate comparison of results obtained in widely separated parts of the country.)
(b) The accumulation of carefully made and fully detailed large-scale geophysical-type maps of fully known structural features, ore-bodies, etc., so that the effectiveness of different geophysical exploratory methods under different conditions may be determined. (Obviously such a series of maps is greatly needed both by persons and companies desiring to have geophysical explorations made and by research workers interested in the improvement of geophysical technique and appliances.)
(c) The accumulation and compilation of geophysical data in such fashion as to make geophysics render maximum assistance in the taking of a reasonably accurate inventory of certain of the Nation's subsurface resources, such as petroleum and artesian water.

The Committee further believes it should be active in negotiating cooperative arrangements leading to the production of a series of regional subsurface geologic maps, which will so far as possible depict the structure and configuration of the upper surface of basement crystallines beneath the whole of the continental United States. Preferably these structural maps should be assembled on the same scales as are to be used in the geophysical compilations.

It seems reasonable to expect that in the execution of the foregoing studies great assis-

tance can be had from the Bureau of Mines, the Coast and Geodetic Survey, and the Geological Survey; from a number of the organizations and institutions represented within the National Research Council; and from or through units of the National Research Council.

It also appears not unreasonable to expect that the objectives of the special committees of the American Geophysical Union and of the Government's agencies for clerical and professional relief can be so coordinated that funds for the support of parts of the work contemplated can be obtained from or through such relief-agencies--an arrangement apparently recommended in the report of the Science Advisory Board to the President.

In conclusion, the Committee has been arranging for conduct by its members of stock-takings of various kinds of geophysical data, and also for new studies--along magnetic-electrical, gravitational-geodetic, seismic, geophysical-geochemical, and hydrological-meteorological lines--and for appropriate cooperation with committees of the Division of Geology and Geography of the National Research Council.

Details of these plans can be given as, and if, desired, but because of the newness of our work and because of the necessarily tentative character of our present decisions we feel it would be wise to postpone the presentation of a really detailed program and plan of work until the 1936 annual meetings of the Union. However, we shall not wait to begin our work until this program has been completely formulated, but will launch studies and will carry them forward as rapidly as our resources permit.

Princeton University,
Princeton, New Jersey

REPORT OF SPECIAL COMMITTEE ON COOPERATION WITH INTERNATIONAL COMMISSION FOR THE STUDY OF TIDAL WAVES

N. H. Heck, Chairman

Perry Byerly H. A. Marmer W. F. McDonald H. F. Reid

The American Committee has representatives from the Weather Bureau, the Hydrographic Office of the Navy Department, the Coast and Geodetic Survey, the University of California, and Johns Hopkins University. It has a permanent function to collect all available information regarding unusual invasions of the shore by the sea. During the year a report was made to the International Commission regarding waves in southern California and also regarding sea-movements accompanying the Panama earthquake of June 1934. At the initiative of the Navy Department, which required better understanding of the possibility of seismic sea-waves accompanying an earthquake like that of Long Beach in 1933, the Chairman compiled a list of known tidal waves of history and it was published in the Bulletin of the International Commission as a contribution of the Committee.

Suitable forms for reporting such waves are in the hands of proper persons along the coast, and forms are available at Washington to be sent as needed. The various agencies represented on the Committee have instructed their personnel to make reports when such phenomena are encountered.

U. S. Coast and Geodetic Survey,
Washington, D. C.

REPORT OF SPECIAL COMMITTEE ON JOURNAL OF GEOPHYSICS

Frank Wenner, Chairman

H. G. Avers C. N. Fenner J. A. Fleming W. R. Gregg H. A. Marmer C. S. Scofield

The Committee--consisting of the chairmen of the seven sections--appointed to consider the possibilities of establishing a Journal of Geophysics finds that there is a great need for additional facilities for the publication of geophysical papers, especially in the fields of hydrology and seismology, and that, all told, the amount of material available seems to be sufficient for from 1000 to 2500 printed pages annually. Inasmuch as the cost per copy, where the number of copies is relatively small, is more or less inversely proportional to the number, first consideration was given to the possibility of securing a substantial number of subscriptions outside the membership of the Union. If the various geophysical organizations of the

country, excluding those interested primarily from a commercial standpoint, would each subscribe for its membership, this would furnish a nucleus of a few thousand subscribers and would justify a detailed study of a procedure for financing, printing by the usual process, and distributing a monthly journal.

Furthermore, by adopting a well-selected format and pooling the contract for printing, distribution, and the handling of cash subscriptions with that of other societies using the same format, a substantial saving in these items could be effected. Accordingly, the American Meteorological Society and the Seismological Society of America were approached with the view to getting them to discontinue their publications and contribute what they are now putting into these publications in return for subscriptions to a Journal of Geophysics for their members. However, the American Meteorological Society replied promptly that they did not wish to give up their publication, and after several months the Seismological Society gave a similar reply.

For an edition of 1500, or sufficient to meet the needs of the Union, and limited to papers originating within the Union, the offset- or planograph-method of reproduction seems to be the most suitable. As compared with printing from type, reproductions of line-drawings, and of halftones, the offset-method has the following advantages: (1) The cost would be from one-half to one-third as much; (2) In case all copy were prepared for the printer in one office, it would provide a more uniform and more economical composition; (3) it would obviate proof-reading, except in the typewritten copy, and would greatly reduce the number of errors, especially in tabulated material; (4) it offers the possibility of varying the size of type, the use of originally tabulated material, and other advantages without much, if any, increase in the cost. A matter of considerable importance is that the quality of planograph-work is being continually improved. For an edition of 1500 and the equivalent of 100 pages per month, the cost, including the preparation of copy for the printer, would be approximately $5000 per year. If this were met entirely by the members of the Union, it would require increasing the dues to about $10 per year. One possibility of obtaining financial assistance from outside the Union is being investigated, but as yet nothing can be reported.

In general, the cost of publication of a scientific paper should be considered as a part of the cost of the investigation and should not be borne either by the author or by the individual who, for personal reasons, might like to read it. It is to the interest of the institution in which the paper originates that it be of high quality, properly published, and suitably distributed. In general, papers should not be considered for publication unless approved in the institution of their origin by someone other than the author, and this approval should involve the assurance of proper editorial supervision and, when practicable, an obligation to defray a reasonable part of the cost of printing and distributing. Incidentally, in most cases, this would reduce the length of the paper, improve its quality, and would place the larger part of the cost of the editorial work where it properly belongs.

In conclusion, the Committee wishes to express its appreciation of the interest of many of the members of the Union and of the active cooperation, especially of Professor Field, Captain Heck, and the General Secretary.

SYMPOSIUM ON THE EARTH'S OUTER ATMOSPHERE

THE ABSORPTION OF LIGHT IN THE ATMOSPHERE AND ITS RELATION TO ATMOSPHERIC OZONE

Oliver R. Wulf

(Abstract)

In the high atmosphere the absorption of solar radiation leads to fluorescence and to persistent ionization and molecular dissociation. The absorption is almost entirely in the far ultra-violet. The degree of ionization and dissociation decreases and the degree of molecule formation increases in passing to lower altitudes, since these in general depend oppositely on collisions. At lower altitudes collisions permit frequent recombination and also the formation of new molecules which introduce new absorption. This absorption by the new molecule may in general lead to its decomposition thus setting up a photochemical steady state--the outstanding example in the atmosphere is that of ozone. Ionization will be confined chiefly to high altitudes and new molecule formation to low altitudes, not so much because of the altitudes at which the respective absorptions occur but rather because of the difference in atmospheric density. Intense absorption by oxygen in the intermediate altitudes leads to inconsiderable amounts of ozone. Moreover, the amount of new molecule formed in a photochemical steady state depends not so much upon the intensity of the absorption of the producing wave-lengths but upon the ratio of the intensities of the producing and decomposing wave-lengths. In a gas distributed exponentially with height, as in a gravitational field, the form of the curve, absorption versus height, is the same for all values of the absorption-coefficient; the curve is simply transposed in height. Thus it comes about that in the production of ozone, not the strongly absorbed radiation which is absorbed at great altitudes, but the very weakly absorbed radiation, which penetrates deeply, is the important radiation in its production. It has been somewhat lost sight of that active wave-lengths, extremely weakly absorbed by oxygen but carrying as much or indeed greater total energy, are absorbed just as completely but at low altitudes as those possessing high absorption-coefficients which are absorbed at high altitudes. In this connection the pressure-dependent absorption in oxygen is also important.

Contrary to earlier beliefs that the ozone lay more or less as a layer at, for example, a height of 50 km, recent experimental results show that it lies well below this, that it is moreover rather broadly spread over a range of altitudes as would be expected from the above theoretical considerations, and furthermore that it extends in definite amounts even down to the Earth's surface. The principal variations occur in the middle and lower regions of this distribution. It is important that the general character of the distributions as given by the methods using the so-called "Umkehr effect" has been at least roughly confirmed by registering apparatus in free-balloon flights in which simply the total ozone above the balloon at different heights was measured.

The measurements of the ozone-content of the air at the Earth's surface have led to another important result in that they indicate the presence of one or more further absorbing gases. An oxide of nitrogen seems a reasonable possibility. The presence of such a chemically active gas as ozone (and an oxide of nitrogen also if present), which is probably rapidly removed from the air through contact with the vegetated and populated portions of the Earth's surface, would seem to indicate that its rate of production in the steady state is relatively high. If the rate of supply is thus not inappreciable, such a gas might be of some biological importance despite its very low concentration.

Bureau of Chemistry and Soils,
Washington, D. C.

THE IONIZATION OF THE EARTH'S UPPER ATMOSPHERE

L. V. Berkner

The development of the experimental technique of radio measurements of upper atmospheric ionization during the past few years has greatly enhanced our knowledge of this region of the Earth's atmosphere. This region is now commonly termed the ionosphere. The radio methods of observation are based upon the phenomenon of refraction of electromagnetic waves in a medium containing free charges. The index of refraction of such a medium to the electromagnetic wave is dependent upon the number of charges in the medium, their mass, and the frequency of the propagated wave. The medium is therefore dispersive, and the higher frequencies, which are less deflected, are more penetrating. If the angle of incidence at the medium and the total deflection

of the wave is known, the numbers of charges of any given mass required to give this deviation can be calculated, and a numerical value of ionization can be thus obtained. This number is usually expressed in equivalent numbers of electrons, although it must be understood that if particles of greater mass are present, a greater number of such particles will give, in general, similar effects. If the motions of the particles in the Earth's magnetic field are considered, however, a limiting ratio of electrons to heavier particles can be determined. In this way it is also possible to ascertain information concerning the strength of the Earth's magnetic field in the ionized region.

Only the most widely used method due to Breit and Tuve will be mentioned here, although the skip-distance method of Taylor and Hulburt, and the frequency-change method of Appleton and Barnett have proven capable of excellent results. The experiments are usually conducted with a radio transmitter and receiver either side by side or very near together so that the angle of incidence is effectively normal. Calculation of the numerical values is thus simplified. A pulse of about 100 microseconds is transmitted, and the time required for each reflection is observed. From these data a virtual height of the refracting medium can be calculated. If the observing frequency is increased, the wave penetrates more deeply into the ionized region before refraction. Finally at high radio frequencies, penetration through the whole region of ionization occurs. From these observations it is possible to calculate an equivalent ionization for each virtual height observed. In practice, the frequency is slowly swept through the frequency-range in which reflections are returned and the results are recorded on sensitized paper. For each sweep through this frequency-range, one set of data is obtained describing the distribution of ionization in the ionosphere directly overhead. This may be accomplished step by step manually, or continuously and automatically by the method devised by Gilliland. An alternative method which, though more simple, yields much less information, records the changing virtual-height of a given ionization as observed on a single frequency.

An attempt to describe the ionization of the upper atmosphere in the short time available must be limited to the most outstanding phenomena observed, leaving more intricate details unmentioned. The ionosphere does not consist of a single homogeneous region of ionization as might be inferred in absence of specific evidence. Instead, the density of ionization fluctuates with height, causing in effect the existence of several distinct regions which, because of their reappearance day after day, can be quite definitely classified. We find that at night two general regions of ionization are apparent, while in the daytime, with small zenith-angles of the Sun, three regions are predominant. This is understood more clearly by reference to a figure showing curves of equal ionization, or iso-ionic curves, which were drawn from data taken at the Huancayo Magnetic Observatory in Peru of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, for particular days. The lowest, or E-region, has a minimum virtual height of approximately 100 km. The second, or F-region, as observed at night, is above the E-region and has a virtual height of roughly 250 km. With the advent of sunlight, the virtual height of this region decreases, and, as the zenith-angle becomes small, the region separates into two distinct ionized regions; the lower, or F_1-region, sinks to a virtual height of about 180 km, while the upper or F_2-region rises to virtual heights of 300 km or higher. Toward sunset these two regions merge, forming the night F-region.

Consideration of the changes of ionization with latitude and season has given further information of the distribution of this ionization. Studies at Huancayo show that a distinct separation of the F_1- and F_2-regions usually occurs with zenith-angles of less than about 40°, while in areas where the zenith-angle is greater than about 40° these two regions are observed to merge into the single F-region. Studies at Washington show that during the winter when the noon zenith-angle is large, separation is hardly apparent, while during the summer with smaller zenith-angles, separation appears. Figure 2, drawn from data taken at Huancayo and Washington, serves to illustrate this distribution. Thus the F_2-region appears as a sort of a circular "bulge" under the Sun, while the F_1-region below it is depressed some 50 to 70 km below the level of the surrounding F-region. These conditions are not repeated exactly from day to day, for the zenith-angles at which separation is distinct are found to vary considerably at a particular station. This separation is also apparently a function of the rate of change of zenith-angle, so that the area described is apparently elongated in a north-south direction.

Variations of the maximum ionization of these various regions may be classified into four general types, namely, diurnal, annual, sporadic, and long-period. In discussing these variations it is profitable to consider the general characteristics of each region individually, for, as may be expected, the phenomena in regions of very different density and height are quite different. The Huancayo observations show that at the equator the E-region has a virtual height which ranges from 95 to 105 km with only small changes from day to night. The investigations of Gilliland, Kirby, and Judson of the Bureau of Standards, of Appleton, Ratcliffe, and Naismith in England, and of the Department of Terrestrial Magnetism in Western Australia show that the height

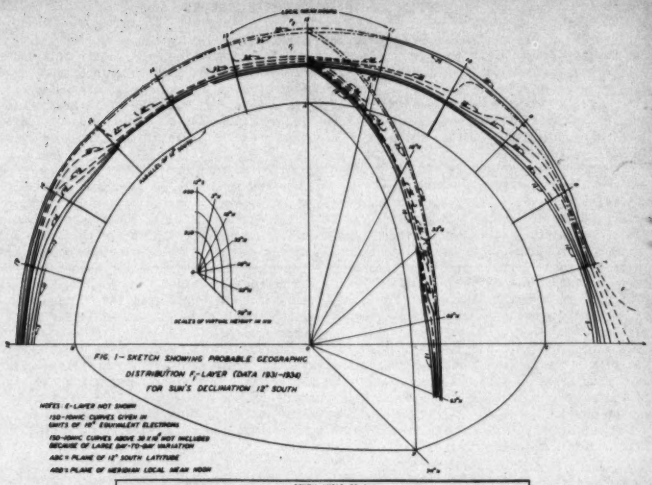


FIG. 1 — SKETCH SHOWING PROBABLE GEOGRAPHIC DISTRIBUTION F_2-LAYER (DATA 1931–1934) FOR SUN'S DECLINATION 12° SOUTH

NOTES: E-LAYER NOT SHOWN
130-IONIC CURVES GIVEN IN UNITS OF 10^5 EQUIVALENT ELECTRONS
150-IONIC CURVES ABOVE 30×10^5 NOT INCLUDED BECAUSE OF LARGE DAY-TO-DAY VARIATION
ABC = PLANE OF 12° SOUTH LATITUDE
ADD'S PLANE OF MERIDIAN LOCAL NOON

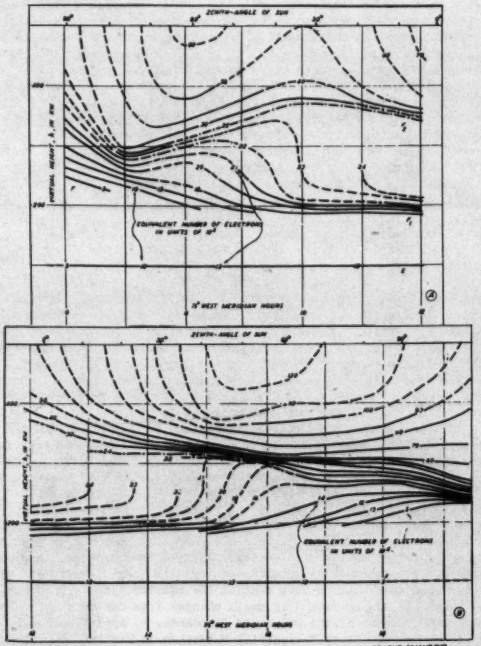

ZENITH-ANGLE OF SUN
VIRTUAL HEIGHT, h'M KM
EQUIVALENT NUMBER OF ELECTRONS IN UNITS OF 10^5
12° WEST MERIDIAN HOURS
A
ZENITH-ANGLE OF SUN
VIRTUAL HEIGHT, h'M KM
EQUIVALENT NUMBER OF ELECTRONS IN UNITS OF 10^5
12° WEST MERIDIAN HOURS
B

FIG. 2 — 150-IONIC CHART FROM SIMPLIFIED VIRTUAL-HEIGHT VERSUS IONIZATION GRAPHS PHANCARD MORNING FEBRUARY 14, 1934 (A); AFTERNOON FEBRUARY 28, 1934 (B)

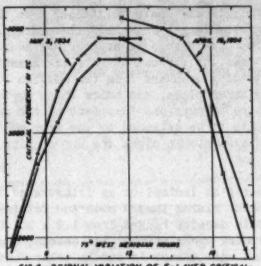
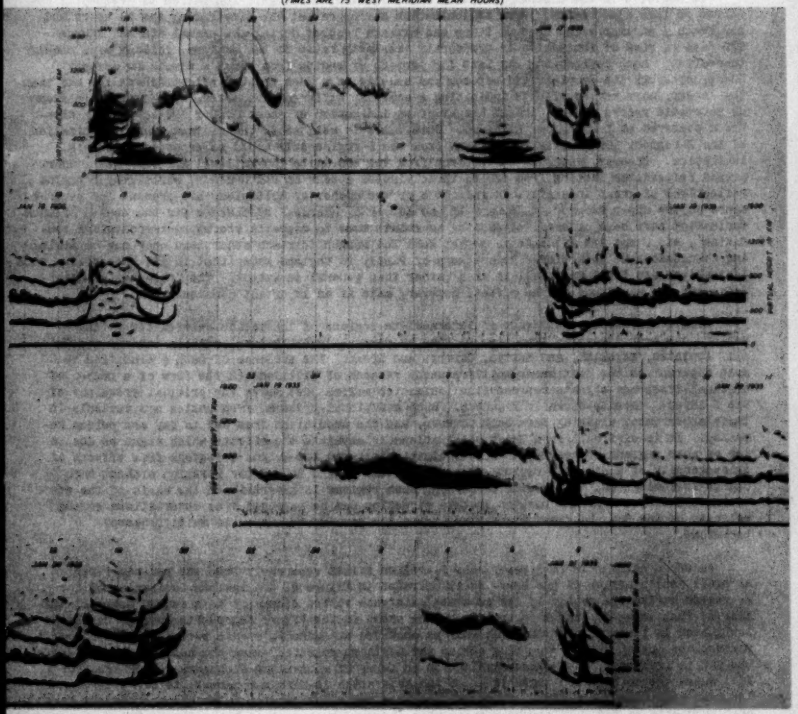


FIG. 3 - DIURNAL VARIATION OF E-LAYER CRITICAL-FREQUENCY LIMITS

FIG. 4

DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION OF WASHINGTON
AUTOMATIC RECORDS OF IONOSPHERE FOR FIXED FREQUENCY 4797.5 KC, KENSINGTON, MARYLAND
(TIMES ARE 75° WEST MERIDIAN MEAN HOURS)



of the E-region becomes more variable at greater distances from the equatorial zone, the heights ranging from 95 to about 140 km with larger changes from day to night. In making any comparison of the virtual height of a region from day to night, certain sources of possible misapprehension must be mentioned. In the daytime, the virtual heights are measured through certain ranges of high ionization of a region extending downward from the maximum ionization to a region in which complete absorption of the wave takes place, and below which further measurements are impossible. At night this maximum decreases to perhaps one-twentieth of its daytime value and absorption-limitation allows the measurements to be extended to the very much lower values of ionization. The virtual heights of a region measured at night are for a quite different value of ionization than those measured during the day.

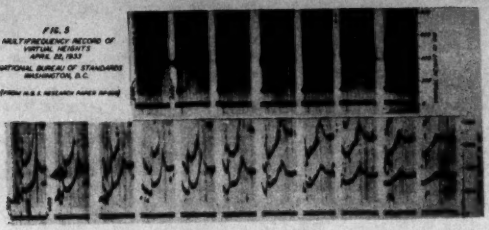
The diurnal variation in E-region ionization as illustrated in Figure 3 is apparently a function of the Sun's zenith-angle, rising toward noon and falling in general through the afternoon and night. The maximum ionic density ranges from 1.2×10^5 to 2.0×10^5 equivalent electrons per cubic centimeter depending upon latitude and season, excepting the polar regions. From this it may be inferred that this change is due to solar radiation. The results of the observations during the eclipses of 1932 and 1935 confirm this conclusion and show that the major portion of the ionization of the E-region must be a radiation from the Sun travelling at the velocity of light, and therefore most probably ultra-violet light.

In addition to the diurnal variation of ionization, a sporadic ionization is frequently observed in this same region. Such an ionization may appear at any time during the 24 hours and may reach a maximum value several times the maximum reached during the normal diurnal change. The rate of rise of ionization is ordinarily extremely rapid to the maximum, falling more slowly thereafter. Such ionizations may last for periods extending from about a minute to several hours, although the short-period effects are usually at a much greater height (about 150 km) than the longer, more marked effects indicating a somewhat different character. In Figure 4 is shown an automatic record of the virtual height of an ionization of about 2.85×10^5 equivalent electrons observed at Kensington, Maryland. This value is well above the maximum diurnal ionization of the E-region. Ordinarily reflections from the F-region only would be expected from this ionization. However, sporadic ionizations from the 100-km to 150-km level are observed. Short-period reflections lasting from one to three minutes appear on all records, while longer period reflections of great intensity, as indicated by the number of multiples, are present for several hours on the upper records of January 16 and 18, 1935. Various hypotheses for the causes of such ionization have been offered, attempting to relate them to magnetic storms, meteorological conditions, etc., but the evidence is as yet much too meager to reach other than what may be misleading conclusions at this time. Recent work of Pawsey in England shows that in all probability such ionizations are local and small in area rather than general in extent. The frequency of occurrence and the magnitude of the effect, however, make it an important consideration.

Possibility of the existence of intermediate regions of ionization between the E- and F-regions has been suggested from time to time by several investigators, notably Schafer and Goodall, Appleton, Naismith, and Martyn, Cherry, and Green. The evidence of such a condition is most apparent on the continuous multifrequency records of Gilliland in the form of a number of critical-frequency effects representing ionization maxima just above the critical frequency of the E-layer. This is shown in Figure 5. Such additional critical frequencies are variable in their appearance, changing from hour to hour, and the conditions from day to day are seldom repeated. It is difficult from these observations to separate the effects which might be due to two or more regions of nearly the same ionization between the E- and F-regions from effects of inhomogeneity of a single E-region which must extend upward toward the F-region without much change in ionization. A decision concerning such regions is uncertain on the basis of the existing evidence. More information in this direction can be expected from observations during eclipses of the Sun and from observations using the continuous automatic multifrequency-technique.

As shown earlier in this paper, the F_1-region exists separately from the general F-region at small zenith-angles of the Sun. As illustrated in Figure 6, the maximum ionization of the F_1-region during the period of its separate existence varies diurnally in a manner somewhat similar to that shown for the E-layer. Each line shown in the Figure represents average values of ionization in terms of critical frequency as observed at Huancayo over a period of one to two months, the lowest values occurring during the northern solstice, when the noon zenith-angle of the Sun is greatest. The maximum ionization in terms of equivalent electrons ranges from 1.8×10^5, where the noon zenith-angle is great and separation is hardly apparent, to 2.6×10^5, where the noon zenith-angle is zero. These values check for all latitudes at which observations have been conducted so far. It has been frequently observed that maximum intensity of the F_1-layer has decreased with magnetic disturbance, but again the data are too meager to reach a definite conclusion.

FIG. 5
MULTIFREQUENCY RECORD OF VIRTUAL HEIGHTS
APRIL 20, 1933
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C.
(FROM N.B.S. RESEARCH PAPER RP 559)



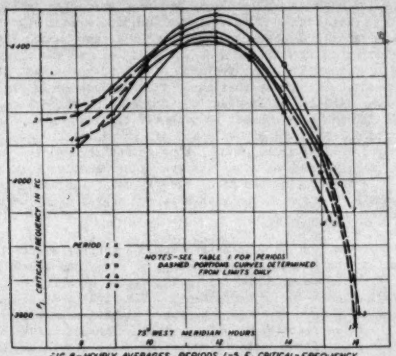


FIG. 6—HOURLY AVERAGES, PERIODS 1-5, F_1 CRITICAL-FREQUENCY
HUANCAYO, 1933-1934

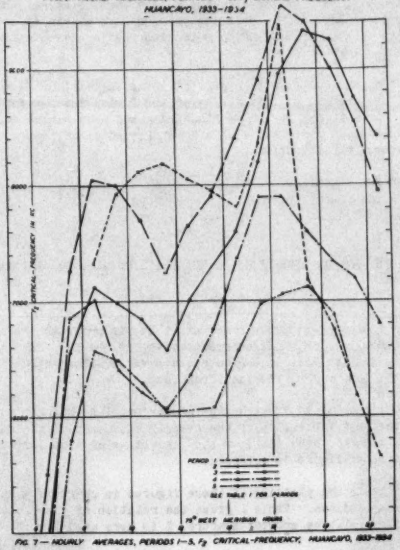


FIG. 7—HOURLY AVERAGES, PERIODS 1-5, F_2 CRITICAL-FREQUENCY, HUANCAYO, 1933-1934

The diurnal variation of maximum ionization of the F- and F_2-regions is not simple and offers much room for speculation. The ionization of the F-region decreases generally during the night--with certain interesting exceptions suggested by Kanzi and shown by Gilliland during which quasi-sporadic night rises in F-region ionization are observed with some degree of regularity. In the latitude of Washington during December, when the F-region does not distinctly separate, the maximum ionization is usually reached within one to three hours after noon, while in June, when separation is distinct, the maximum is reached in the late afternoon or evening. Throughout the year at Huancayo, however, the rapid rise in F-region ionization with sunlight (becoming F_2-region ionization at small zenith-angles) is usually followed by a decrease to a minimum before noon, with a rise to a greater maximum later in the afternoon again followed by a decrease as night conditions set in. This is illustrated by the average values shown in Figure 7. These daytime observations of the F- and F_2-regions show two outstanding characteristics, namely,a variability of as much as two to one in maximum ionization from day to day with a general lack of any detailed repetition of form of variation, and a much higher indicated maximum noon ionization at Washington and at Watheroo during the larger zenith-angles, which is contrary to what may have been expected from the form of variation of the lower layers. It is, as yet, impossible to map out any general surface features of the F_2-region as has been the case with the lower layers, because of these complications. It seems extremely significant, however, that this high ionized region, existing as it does in a space above which there can be little absorption in the ultra-violet, should be subject to such erratic changes as compared to the lower regions. Furthermore, the observations of maximum December ionization of the F-region at Washington and Huancayo over a period of years shows a long-period change with the minimum average values observed near the sunspot minimum. Such changes are of comparatively large magnitude and are immediately suggestive of a direct relation to changes in solar radiation. A conclusion can hardly be reached, however, until observation has been extended over a much longer period of time at more locations.

Two other aspects of the problem must be mentioned. Further stratification of the F_2-layer is frequently observed at both Washington and Huancayo. Kirby and Judson have made a study of this effect and believe that some evidence exists indicative of a further ionized region or G-region above the F_2-region under some circumstances. The night appearance of reflections from high virtual heights, such as were shown in Figure 4, has been reported by a number of investigators. These have been interpreted by Hiano as evidence for additional high layers which are uncovered or appear at night. These latter effects, however, might also be accounted for on the basis of reflections coming in from the side due to the possibility of what might be termed "edge-effects" under such conditions. Definite proof of the origin of such effects awaits direction-measurements of the reflections to determine whether these reflections come from above or from the side.

In conclusion, I wish to express my appreciation to the various investigators upon whose work I have drawn in preparation of this review of the field, and particularly to the staff of the radio section of the National Bureau of Standards, who have conducted their investigations consistently over a period of years and who have maintained close cooperation with our staff at the Department of Terrestrial Magnetism.

Department of Terrestrial Magnetism,
Carnegie Institution of Washington
Washington, D. C.

ON THE CORRELATION OF RADIO TRANSMISSION WITH SOLAR PHENOMENA

A. M. Skellett

Short-wave radio character-figure--It appears that, in order to get a character-figure for short-wave radio transmission, which is representative for the day, data must be taken over the whole 24 hours. Since the New York to London short-wave telephone-circuits are in practically continual use, suitable data may be obtained from them.

It has been found that the field-strengths of the received signals taken at regular intervals do not furnish the best indication of the overall character of the day. If, however, the ratio of uncommercial time to total time, or the percentage of time lost to traffic is taken, a fairly good daily character-figure is obtained.

In order to facilitate the plotting of these figures in chart-form they were reduced to four classifications or group-indices. Table 1 gives the relation of these character-figures, T (since the letter R is used for relative sunspot-numbers, T is here used for the radio character-figure

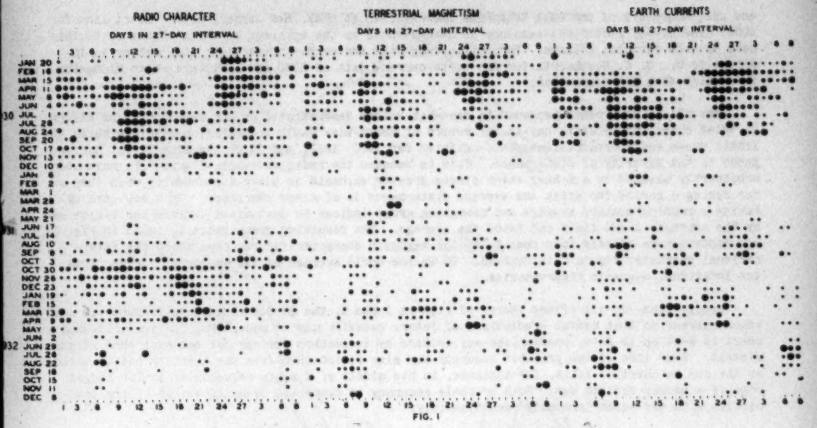


FIG. 1

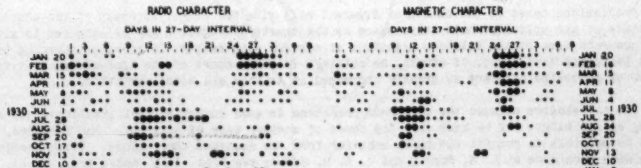


FIG. 2

designation) and the group-indices (T_1).

Figure 1 shows these group-indices arranged to bring out the 27-day recurrence-tendency. This Figure shows a day-by-day record of short-wave radio transmission over the North Atlantic Ocean of terrestrial-magnetic activity and earth-current activity for 1930, 1931, and 1932, demonstrating the 27-day recurrence tendency. The size of dot corresponds to the severity of disturbance. The magnetic indices were derived from the daily ranges of horizontal intensity as recorded by the United States Coast and Geodetic Survey at the Cheltenham Observatory (Maryland) and those for earth-currents were obtained in New York State over lines of the American Telephone and Telegraph Company for 1930 and 1931

Table 1--Relation of character-figures T and group-indices T_1

T_1 Classification	T Percentage time uncommercial
0	0 to 24
1	25 to 49
2	50 to 74
3	75 to 100

and the laboratory of the Bell Telephone Laboratories at Deal, New Jersey, over a short line for 1932. The 27-day recurrence-tendency is demonstrated by the apparent bunching of the spots into more or less vertical columns. Terrestrial-magnetic and earth-current data (the writer is indebted to Dr. G. C. Southworth for the earth-current data of 1930 and 1931) are shown alongside in similar form for comparison.

The 27-day recurrence-tendency is somewhat better demonstrated on the radio chart of Figure 2, which shows the relative day-to-day record of short-wave radio transmission over the North Atlantic Ocean and terrestrial-magnetic activity for 1930, 1931, and 1932; the size of dot corresponds to the severity of disturbance. This is because the radio character-figures (T) have been arbitrarily altered in a manner which places greater emphasis on minor disturbances when they occur during a period for which the average disturbance is of minor character. This was done by taking a running monthly average and assigning group-indices to deviations between the limits set by the average, 1-1/2 times and twice the average. The resulting group-index T_2 (used in Fig. 2) corresponds more closely than does T_1 to the magnetic character-figures from which the international character-figure C is derived. (C is the world average of the character figures from the individual magnetic observatories.)

Predictions--In all of the charts of Figures 1 and 2, the 27-day recurrence-tendency is well enough marked so that useful predictions of future behavior may be made. For instance, if such a chart is kept up to date, predictions may be made by inspection for any day not more than 27 days distant. Some idea of the probable accuracy may also be obtained from the chart by noting whether the day in question falls, for instance, in the middle of a major sequence or on the ragged edge of a poorly defined one. Such probable accuracy is expressed by modification of the prediction with the words "probably" and "possibly."

Predictions based on the charts of Figure 1 will give the better forecast of the absolute magnitude of the activity while those based on the charts of Figure 2 may be expected to give a more accurate idea of the relative magnitude of one day with respect to those neighboring to it. These two properties could, of course, be obtained from one chart of the type of Figure 1 if the number of group-indices were so greatly increased as to show all minor variations.

The correlation between the different phenomena is good enough so that predictions of activity of one nature may be made from the chart of another type of activity. For instance, it would be possible to predict the radio behavior from the magnetic chart alone. (Such predictions have been made by R. M. Morris and W. A. R. Brown; see Proc. Inst. Radio Eng., v. 21, pp. 63-80, 1933.) This method has been found to be of the same order of accuracy as that using the radio chart alone. The reason for this is not, obviously, that the correlation for the radio and magnetic data is perfect but probably that the radio data as they are obtained at present are subject to greater inaccuracy than the magnetic and such inaccuracy apparently just about compensates for the imperfect correlation between the two phenomena.

In order to determine which type of data may be expected to prove the more useful in making predictions of radio behavior, the correlation-coefficients between magnetic and radio data and earth-current and radio data were determined. These are given in Table 2.

Table 2--Correlation-coefficients

Year	Magnetic and radio	Earth-current and radio
1930 (first half)	+0.66	+0.76
1930 (whole year)	+0.63	+0.67
1931	+0.30	+0.44
1932	+0.44	+0.46
Average	+0.46	+0.52

These coefficients indicate that predictions based on earth-current measurements should prove the more accurate. Whether this is true can only be determined, however, by a more comprehensive and detailed study of the data. They also indicate that the correlation is best when the radio disturbances are greatest, which is, fortunately, also the time when predictions are needed the most.

Daily predictions of the behavior of the radio circuits from either the radio or magnetic chart have been correct 62 per cent of the time. Similar predictions of the magnetic data from the magnetic chart have been correct 71 per cent of the time. These figures have been determined solely on the basis of disturbed or undisturbed and modification of the forecasts by the words probably and possibly have not been taken into account.

This method of making predictions, even in its present state, is of definite use commercially. Special forecasts of the same nature have proven useful in planning certain experimental studies. Among the latter were those made for the magnetic and radio behavior during the solar eclipse (A. M. Skellett, Science, v. 76, p. 169, 1932) of August 1932 and the Leonid Meteor

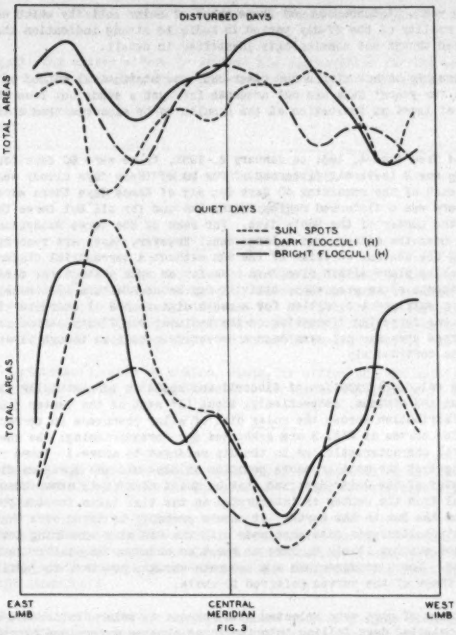


FIG. 3

shower (A. M. Skellett, Science, v. 76, p. 434, 1932) of November 16, 1932.

Terrestrial-solar correlation--The solar data for correlation-purposes were obtained mainly from the spectrohelioscopic observations made at Deal, New Jersey. They were supplemented by data published by the observatories mentioned below.

Well-defined sequences of activity of approximately 27-day period are apparent in both the solar (see below) and terrestrial (Figs. 1 and 2) data. An attempt to link these two phenomena together in a cause-and-effect relationship was not, however, very successful. For several well-marked radio (and magnetic) sequences it was found that no single type of solar activity could be identified in such a manner as to exhibit a clear-cut relationship. For some of the sequences there was some form of solar activity near the center of the Sun at the time of each radio disturbance but such activity varied between recurrences in heliographic latitude and longitude and in kind (bright and dark hydrogen-flocculi, activity of these as shown by radial velocities and rapid motions, and sunspots).

A similar indefinite result was found by starting with the solar observations. For instance, an area on the Sun approximately in heliographic latitude of +10° and longitude of 315° to 329° exhibited the presence of either hydrogen-flocculi, prominences, or sunspots or combinations of these on each transit across the face of the Sun from October 21, 1932 to February 9, 1933, a total of five transits. Sunspots appeared in this region on the last four transits and their identity over this period of time was noted at Mt. Wilson Observatory (Proc. Astr. Soc. Pacific, v. 45, pp. 52-54, 1933). From a spectroheliogram taken at the Solar Physics Observatory at Cambridge, England, December 12, 1932, C. P. Butler (Mon. Not. R. Astr. Soc., v. 93, pp. 174-175, 1933) determined that this disturbance extended over a great area some 30° in diameter. Although the times of central meridian crossing of this area fall within a well-defined sequence on the radio chart (between days 6 and 9 on the left at the bottom of Fig. 2) the absence of activity on this solar area for earlier recurrences of the radio sequence tends to vitiate the re-

lationship between radio disturbances and those types of solar activity which were observed. Nevertheless, the reality of the 27-day period in radio is strong indication that solar activity is responsible, even though not convincingly identified in detail.

If the relationship is not simple and clear-cut, the statistical method of correlation must be resorted to. A few years' data are not adequate for such a study but from them it was attempted to obtain at least an indication of the results to be expected from a larger amount of data.

For the period from June 4, 1931 to January 6, 1933, there were 80 days for which the radio character-figure T_2 was 3 (severely disturbed). For 20 of these days cloudy weather prevented observation. For each of the remaining 40 days (on six of these days there were no spots visible on the Sun) there was a disturbed region on the Sun and for all but three this active region was within 30° of the center of the Sun's disc. For each of the three exceptions this disturbed region, though not near the center, was a large one. However, cases are recorded of such active solar areas passing the central meridian of the Sun without a terrestrial disturbance of appreciable magnitude taking place within five days. As far as such statistical data go, we might assume that the presence of an area whose activity may be seen with a spectrohelioscope is a necessary though not a sufficient condition for a radio disturbance of character-figure $T_2 = 3$. On the other hand, the foregoing discussion on the basis of the 27-day period suggests that detection of a disturbed area has not even been a necessary condition though it might be if the observations were made continuously.

A study of the solar distribution of flocculi and spots on terrestrially disturbed and quiet days shows a maximum and minimum, respectively, about 13° west of the center (one day past); see Figure 3 showing distribution across the solar disc of solar phenomena on terrestrially disturbed and quiet days. (The curves of Fig. 3 are corrected for foreshortening; the uncorrected curves show the same general characteristics as to the dip referred to above.) These curves are interpreted as indicating that the most probable position of flocculi and spots on disturbed days is 13° west of the center of the solar disc and that on quiet days it is other than in this region. The one-day interval from the center is interpreted as the time taken for the propagation of the disturbance from the Sun to the Earth. It should probably be noted here that the positions taken from the spectroheliocopic data were made with the aid of a measuring device used visually at the instrument and are not likely to have as great an accuracy as similar measurements made on spectroheliograms. These measurements are accurate enough, however, to justify confidence in the reality of the shape of the curves referred to above.

A number of groups of days were selected with respect to solar disturbance or lack thereof. The percentages of selected days falling into the three classes determined by radio character--severely disturbed, moderately disturbed, and quiet--were compared with the average distribution of all days falling into these classes. A positive correlation was found for the severely disturbed days ($T_2 = 3$) for both the solarly active selection and the solarly quiet selection of days (actually a negative correlation here) but not generally for the moderately disturbed ($T_2 = 2$ or 1) and quiet ($T_2 = 0$) days. The same study for the magnetic data gave a positive correlation throughout for the solarly active days.

Similar studies were made of the radio data for the presence of flocculi exhibiting radial velocities. These are generally short-lived phenomena and most such occurrences must necessarily be missed since the Sun is actually under observation for only a small per cent of the time. The data in this case were very meager but gave a positive correlation.

This study was continued for days on which flocculi with radial velocities were observed near the center of the Sun. These gave the best correlation of all, though here the number of days was so few (actually only 13) as to place little faith in the result. It is mentioned here, however, because it supports the idea that could the solar disc be watched continually on a world-wide program of observation, as Hale (Astroph. J., v. 73, pp. 380-412, 1931) has suggested, to record all solar outbursts and so to increase the completeness of the solar data until it approaches that of the terrestrial data, it seems likely that considerably more success might be obtained in determining the solar-terrestrial relationships.

It is of interest to record the data for the most severe radio disturbance and magnetic storm (May 29, 1932) experienced during this period. They occurred during the passage across the face of the Sun of one of the most active solar regions observed. The largest radial velocity that has been measured since observations were begun was exhibited by a mass of gas in this region. The magnetic storm was accompanied by an aurora visible as far south as Mexico. The gases over this solar region exhibited extreme turbulence on the face of the Sun, and when it had reached the western limit an enormous prominence of great brilliancy and activity was seen

to blow off into space. It was over 100,000 miles in length and completely disappeared within an hour.

Acknowledgment--The writer wishes to express his appreciation for the constructive criticism and counsel of J. C. Schelleng throughout the course of this investigation.

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THEORY OF THE IONOSPHERE

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(Abstract)

The atmosphere above about 180 km is heated by the absorption by molecular oxygen of the spectral region from 1200Å to 1800Å of sunlight. Calculation indicates that the temperature of the atmosphere from 180 km to 300 km may increase 50° per hour in the daytime, which causes molecular oxygen, and possibly nitrogen, to dissociate into atoms. Due to the heating and dissociation there is a marked daily expansion, and nightly contraction, of these outlying levels.

For a static atmosphere, with no motion, winds, or diffusion, the density of y of the ionization of any region during the day is related to the zenith-angle Z of the Sun approximately by

$$y = y_0\sqrt{\cos Z} \qquad (1)$$

if the recombination-coefficient of electrons and positive ions is of the form given by the three-body collision-theory of Sir J. J. Thomson, and if the ultra-violet light of the Sun is the cause of the ionization.

The recently published ionosphere-data of the National Bureau of Standards and of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington are the most comprehensive and accurate which have yet been obtained and constitute the first approach to a world-wide survey of the ionosphere.

The E-region--The hourly average daylight values of y of E agree closely--within 10 per cent--with (1) throughout the year, showing that the solar ultra-violet light is the cause of the ionization and, as expected from theory, that diffusion is unimportant. Sporadic variations of y may be due to winds and to the liberation of energy by excited atoms and molecules.

The F_1-region--The observed diurnal and seasonal curves of y of F_1 are somewhat flatter than those given by (1). Diffusion of the ionization seems adequate to account for the difference between the observed and theoretical curves.

The F_2-region--For F_2 the ionization caused by solar ultra-violet light is modified by the daily expansion of the atmosphere above 200 km and by the winds which result from the expansion. Omitting details it may be stated that the theory gives qualitative agreement with most of the complex daily and seasonal changes in F_2, such as the double daily maximum of y of F_2 at the equator and the noon winter maximum and the evening summer maximum in temperate regions.

It is pointed out that there is an apparent difficulty in accounting for permanent, or quasi-permanent, banks of ionization at or above 250 km, as F and F_2 appear to be. Calculation indicates that diffusion would prevent the formation of ionized strata much above 220 km. If they actually exist at greater heights, probably the present tables of air-densities in these levels, or the recombination-formulae, among other possibilities, may require modification.

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CONDITIONS IN THE UPPER ATMOSPHERE AS INDICATED BY A STUDY OF METEOR-TRAINS

Charles P. Olivier

It has been recognized for a considerable time that the drifts of long-enduring meteor-trains give us our principal direct information about the wind-currents in the upper atmosphere. Since the directions and velocities of these currents, as well as their altitudes, are of great interest and importance in studies dealing with the physics of the upper strata, it is quite worth while to obtain all the data possible. The actual observation of meteors is, however, a purely astronomical problem, and only through this can the train-drifts be derived. The result of such study is therefore one of the happy combinations in which the derived data are valuable directly to more sciences than one.

The American Meteor Society has in recent years laid particular stress upon observations of long-enduring trains, and, thanks to the cooperation of its members and many other observers, we now have information upon a large number of trains which lasted from three minutes to nearly two hours. Unfortunately most observers did not know just what details were wanted and were later unable to recall them with accuracy, if at all. This means that only in a few cases have we been able to make satisfactory complete solutions, while in a few others we can give partial results. But when one remembers for how few meteor-trains in the past have numerical results been derived, each new addition is seen to be of some importance. Before the specific results obtained by the American Meteor Society are presented, however, a brief review of the work done elsewhere will be given. In recent years there has been a great revival of interest in meteoric astronomy in Europe, and results have been published in many languages and in obscure journals. Hence it is very probable that some such work may not be mentioned here.

A very important paper on meteor-trains is the doctoral thesis of Simon Kahlke, at Hamburg, Germany, in 1921 (Simon Kahlke, Meteorschweife und hochatmosphärische Windströmungen, 7 pp., Hamburg, 1921). Unfortunately only a seven-page abstract was printed for circulation, and my remarks are perforce based upon this. He divided the trains into two groups--those between altitudes of 30 km and 80 km, and those of altitude above 80 km. In general, he considers the first group as "smoke"-trains, the second group as the luminous trains seen only at night. Out of 16 available cases below 80 km, he found 11 indicated a wind from east to west, a general direction which he says verifies the facts observed when the dust of Krakatoa was spread by east winds over the Earth. He states, without figures, that there is good agreement also as to velocity of train-drift and spread of dust.

For the night trains many more data were available--44 for Europe and 33 for North America. These, presumably in the stratum at 80-km altitude or higher, gave indeed very differing directions, some coming from nearly every point of the compass. However, by forming a vector-polygon for the 44 European cases, he derived a west wind with a weak northern component. The 33 American drifts also gave a west wind but with a strong southern component. It will be noted that the general directions above and below 80-km altitude are exactly opposite according to his study. The different components for Europe and America may be ascribed to the fact that most observations in Europe were made in the western part while most in America were made in the eastern part; therefore, on both continents the derived data apply primarily to winds near the ocean. The average latitudes for the two groups are quite different. He discards as useless for his purposes the few actual velocities at his disposal, and apparently gives no quantitative estimates.

Looking into the important work of C. C. Trowbridge of Columbia University (New York), who did more than anyone else in his lifetime for the study of meteor-trains, I find that his older cases were included in the discussion by Kahlke. (C. C. Trowbridge, On atmospheric currents at very great altitudes, Mon. Weath. Rev., v. 35, pp. 390-397, 1907; bibliography on meteor-trains and summary of Trowbridge's work are given in a paper by Mabel Weil, Theories on the nature of meteor-trains, with a note on Professor Trowbridge's contributions to our knowledge of meteor-trains, Pop. Astr., v. 30, pp. 524-535, 1922.) For only three cases are velocities given by Trowbridge. They are 196 km/hr from northeast at 87-km altitude, 201 km/hr from south at 97-km altitude, and 97 km/hr which above 80-km altitude indicated a south wind and below 80-km altitude a north one. The drifts of others are given in degrees, but only by assumptions could velocities be derived. Trowbridge's work, however, brought out one result very clearly, namely, that for 13 long-enduring trains for which accurate heights were available, the mean altitude was 89 km. For six of these 13, he was able to find both the upper and lower limits, the averages being 96 km and 82 km, respectively. His conclusion was that only in this stratum were long-enduring trains to be expected, and he developed a theory of phosphorescence to account for their visibility which was dependent upon the low pressure computed for this stratum. This problem--the source of the train's light--needs complete restudy, so only certain aspects of it will be mentioned here.

As to our own results in the American Meteor Society, in the past three years we have been able to solve four train-drifts for both velocity and direction, three of the four being probably fairly accurate. In addition, we have partial results for a number of other cases. The four best consist of two Leonid fireballs observed during the shower of November 16, 1932, one fireball on March 24, 1933, and one on August 21, 1933. The fireball of March 24, 1933, will be discussed at length. The main results for the others are:

No.	Object	Magnitude	Altitude Beginning km	Altitude Ending km
1	Leonid fireball	-3	119	86
2	Leonid fireball	-4	142	73
3	Aug. 21, 1933, fireball	-12±	171	48

The first train had a velocity of 151 km/hr from north-northeast, and it was found that at level 100 km to 105.7 km the wind was blowing upwards at a 35° angle. After several minutes the central part of the train was a ball fully one km in diameter.

The second train, 27 minutes later, at 100-km level showed a velocity of 236 km/hr, with wind from east-northeast; its upward motion made an angle of 55° with the horizontal. Each of these trains lasted about nine minutes. The second after four minutes was an elliptical ball 3.8 km by 1.3 km in size. Another train that same night, of duration 30 seconds, also drifted to the south, but as it was seen from only one station no height or velocity could be computed. All three of these trains appeared over Maryland, showing that in that region on November 16, 1932, between 1:00 and 3:00 a.m. there was a wind in general from northeast to southwest at 100-km altitude, with a strong upward component, and with a velocity of 150 to 250 km/hr.

The fireball of August 21, 1933, was over Tennessee. The train's mid-point had an altitude of 81 km; its limits were 108 km and 57 km; and the wind-direction was from 15° north of west, blowing horizontally at 128 km/hr.

The great Oklahoma-Texas-New Mexico fireball of March 24, 1933, left a train visible in parts for an hour and a half at least, lasting until long after sunrise. The three just discussed were all typical night trains; that of March 24 is more complex by far. However, one section of it--the eastern part--which lasted over an hour and a half between levels 80 km and 100 km, drifted in general south of east, indicating a west-northwest wind of velocity 300 ± 100 km/hr.

For these four cases, for which velocities and directions were both calculated, the directions of two were at right-angles to the other two; also two showed upward components and two moved horizontally. The order of velocity was between 100 and 300 km/hr. These facts make us doubt whether general conclusions as to directions of drifts can be safely drawn until far more cases are studied.

Two other brilliant meteors give us some evidence about trains in the lower atmosphere. The first is the Virginia fireball of December 2, 1931, which came at 6:50 a.m. and whose train lasted over an hour. It was still visible after sunrise. This was probably largely a smoke- or dust-train; the upper end was at 43 km, the lower at 12 km, where the object burst. The drawings did not permit accurate quantitative estimates of drift, but all the evidence points to there being no wind at 16-km altitude, above 16 km a wind to southwest, and below, to northeast. Horizontal currents moved in opposite directions but with very low velocities. The maximum could hardly have reached 15 km/hr. The lower part of the train was W-shaped. This shows that the strata did not have sharp boundaries, an important conclusion borne out by many other cases. The Richmond (Virginia) Weather Bureau Office has kindly given me data for Lynchburg and Richmond wind-velocities on that date. For 7:00 a.m., about when the fireball appeared, these were, respectively, 7 mi/hr from northwest and 3 mi/hr from northeast. The train extended upward between these two stations.

The second smoke-train, that of the Pennsylvania fireball at 6:20 a.m. on February 27, 1935, was also in bright twilight. It lasted at least 15 minutes. As reports are still coming in, no final results have been derived. Enough, however, is known from inspection to affirm variable wind-directions in horizontal strata, but all of small amount. Neither this train nor the Virginia one appreciably shifted as a whole from its original position.

The most remarkable fireball of all here discussed, that on March 24, 1933, had a path about 670 km long, and near its end several meteorites were formed from its debris. It started at a height of 141 km, ended its visible path at 17 km, and exhibited all the phenomena usually con-

nected with a detonating fireball. Every effort was made to derive accurate velocities for the train left by this object. The usual data were supplemented by a photograph by Allen at Trinidad (Colorado) and a whole series by West at Timpas (Colorado), as well as by drawings elsewhere. Unfortunately the photographs were not accurately timed, so their great value is much impaired for calculations of drift, though they remain of extreme interest in other ways.

Briefly, there is no doubt that the main train drifted with a high velocity toward the general direction of east. Its upper and brighter part broke up into three main clouds. On the fundamental basis of observations from Boise City (Oklahoma), these clouds showed a velocity of 280 km/hr with a wind from 40° north of west. From the prints at Timpas as fundamental, the velocity was 273 km/hr with a west wind. The good agreement is mostly fortuitous. From the Trinidad photograph the eastern end of the brightest part of the train was 102 km up at about 5:30. We further know that about five minutes after the meteor passed, the western end of the train was only 25± km high, and about 25 minutes later it was 30± km high. This end faded relatively soon. The eastern half of the train, with a height from 60± km at its western end to 100± km at its eastern end, lasted much over 90 minutes. Making full allowance for all uncertainties, a fair estimate of the drift between 60-km and 100-km altitude was 300 km ± 100 km/hr on a west-northwest wind. This, however, is simply the drift of the train in the direction of its long axis. The main train also shortened along this axis, perhaps due to differential velocities.

The train was complicated by lateral motions of parts, as shown clearly by a drawing made from a station almost in line with the plane of the orbit. Further, the train itself broke up into knots or clouds, and changed both shape and color as daylight advanced. An explanation of all that took place cannot be attempted here, but I will try to point out some of the problems that are presented.

First, we must realize that the original body (or group of bodies, perhaps) was at most only a few feet in diameter. The kinetic energy of its motion, dissipated by the resistance of the air, was enough to produce not only the great train but also violent sound-phenomena heard fully 100 km on each side of the latter part of its path. Fifteen minutes after its passage, the train was in its widest portions fully one degree in diameter as seen from stations whose distance permitted the linear diameter of 7 to 8 km to be deduced. This means that for 4 km on all sides of the original orbit excitation had spread out more or less cylindrically. This lateral expansion was hence of the order of 15 km/hr. As the various parts of the train seem to have existed at heights from 25 to 100 km, the usual division into "smoke-train" and "luminous night-train" seems inadequate or misleading. Apparently we have both phenomena; even some of the same parts of the train were seen at first in an almost dark sky and later in full sunlight. Had the illumination been a mere reflection-phenomenon, however, a different distribution of brightness would have been expected. It is difficult to escape the conclusion that both fine dust and some type of phosphorescence or electric action in gases were agents in producing the observed train.

In this very brief survey the attempt has been made to show the amount and quality of the data now at hand, to mention a few of the problems to which they can be applied. Any attempted explanation of the real causes of the long-enduring visibility of the trains has been omitted, as the theories are incomplete or need revision. Their great importance to meteorology has been brought out, it is hoped, sufficiently plainly to enlist the cooperation and interest of scientists in general in our future attempts to obtain data on such phenomena.

Of one conclusion we can be absolutely certain, however: Meteor-trains prove that wind-velocities between 100 and 300 km/hr are the usual and not the exceptional thing for that stratum in which the long-enduring trains appear at night, and there is good evidence of vertical as well as horizontal motion. Thanks to a grant from the American Philosophical Society, we plan next year at Flower Observatory to undertake a systematic study of existing data and theories and, if possible, to come to somewhat bettter conclusions than could be presented in this paper.

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CONTRIBUTION OF THE COSMIC RADIATION TO THE IONIZATION OF THE UPPER ATMOSPHERE

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On the basis of the earlier measurements of Hess and Kolhoerster, H. Benndorf (Physik. Zs., v. 27, pp. 686-692, 1926, and Wien-Harms, Handbuch der Exper. Physik, v. 25-I, p. 279) considered the effect of the cosmic radiation in producing electrical conductivity in the upper atmosphere. In his theory ions were produced at a rate proportional to the product of the cosmic-ray intensity by the density of the atmosphere and they disappeared by recombination, the coefficient for which was determined by the theory of J. J. Thomson (Phil. Mag., v. 47, pp. 337-378, 1924). Benndorf concluded that a conductivity 10^{10} times that at the Earth's surface could be produced by the cosmic radiation at 100 km. The increase was due to a hundred-fold increase in the cosmic-ray intensity, accounting for a tenfold increase in the number of free ions and a 10^9-fold increase in ionic mobility.

In recent times cosmic-ray intensities have been measured at elevations greater than those reached by Kolhoerster and considerable evidence has been gained regarding the production of secondaries, giving some rational basis for extrapolation of the ionizing effects beyond the levels attained in balloon-flights. Knowledge of the actual state of ionization in the higher layers has also been greatly enriched by the investigations of radio-wave reflections, following the methods introduced by M. A. Tuve and G. Breit (Nature, v. 116, p. 357, 1925) and E. V. Appleton and M. A. F. Barnett (Nature, v. 115, pp. 333-334, 1925). The large diurnal and seasonal variations of the reflecting layers lead to the conclusion that most of the ionization is produced by rectilinearly propagated rays from the Sun and the same conclusion was particularly well established by the 1932 eclipse work of S. S. Kirby, L. V. Berkner, T. R. Gilliland, and K. A. Norton (Bur. Stan. J. Res., v. 11, pp. 829-845, 1933). There is, in fact, no difficulty in attributing all of the observed ionization to the ultra-violet radiations from the Sun, although the evidence would not exclude a small but appreciable contribution from some other source. It is thus of interest, in the light of recent developments, to again estimate the amount of conductivity in the high atmosphere which can be attributed to the cosmic radiation.

Though there may exist additional radiations of cosmic origin in the highest layers of the atmosphere, from the experimental point of view the discussion must be limited to those rays which can be studied by direct electroscope or counter measurements in the lower available regions. Typical, and perhaps the best, intensity-measurements of this kind have been made on free-balloon flights by E. Regener (Nature, v. 132, pp. 696-698, 1933). His instruments were thin-walled electroscopes measuring the rate of production of ions in a gas at atmospheric pressure at various heights up to that corresponding to a barometric pressure of 25 mm. The ionizing effect of the same radiation in the ionosphere can be determined by extrapolation of Regener's curves to the point of zero barometric pressure. Three of Regener's flights resulted in curves which flattened out at about 50 mm to a constant ionization of 300 ions per cc per sec per atmosphere. It is thus reasonable to consider this value as representative of the cosmic-ray intensity at all greater elevations, except where changes in the magnetic field must be considered. (Though not specifically stated in Regener's paper, his flights presumably took place from Stuttgart--latitude 49° north and longitude 8° east.)

Before adopting this value it is well to consider certain arguments which have been advanced relative to such an extrapolation. In the first place, if the primary radiation contains photons which contribute to the ionization only after they have produced secondary electrons by collision with atmospheric matter, it might appear that this process would give rise to a transition-effect in which the ionization would at first increase with depth in the atmosphere. H. Kulenkampff (Naturwiss., v. 21, pp. 25-26, 1933) has pointed out that such a transition-effect would not occur in the Earth's atmosphere because of the action of the Earth's magnetic field. This causes the secondary electrons to circulate about their point of origin in circular orbits and, though the rate of production is proportional to the pressure, their duration, or the number of times they circulate about the point of origin, is inversely proportional to the pressure. Hence the number of ions produced by secondary charged particles is independent of the pressure and is proportional to the intensity of the primary radiation. A similar argument also applies to the ionization by secondary particles generated by corpuscular primaries. On the other hand, if primary corpuscles generate secondary photons which in turn generate tertiary particles, the ionization due to the latter would be proportional to the intensity of the secondary photons at every point and would therefore increase, at first, with depth in the atmosphere. A transition of this nature would tend to give a lower ionization in the outer atmosphere than would be indicated by simple extrapolation of Regener's curves.

As a second consideration, the extrapolation over the last 25 mm of pressure, though a short one on the barometer-scale, is a long one on the scale of geometric distances. Changes in solid

angle due to diminished shielding by the Earth may thus be important. Considering straight-line propagation, the solid angle at 100 km is only 2.8 per cent greater than at the Earth's surface. On the other hand, high-energy secondaries describing circular orbits would be able to enter the electroscope from nearly twice the solid angle at the higher elevations. This effect would tend to increase the ionization somewhat above that indicated by the simple extrapolation.

A third consideration involves the effect of the greater distance from the magnetic center of the Earth, permitting lower energy-radiations of the corpuscular type to reach the higher levels. At the height of 100 km the distance from the center of the Earth is 1.7 per cent greater than at the surface and the lower limit of the energy of incident radiation at all latitudes is decreased 3.4 per cent. In the latitude of 50° Störmer's theory gives 2.5 billion volts as the lower energy-limit for electrons at the Earth's surface. At the height of 100 km the lower limit would be 2.4 billion volts. The intensity at the higher level is thus augmented by the slightly greater energy-range.

Though none of the above effects is susceptible of exact calculation, it is reasonable to assume that they do not account for any very great differences between the ionization at 25-mm and at zero-pressure. The value of 300 ions per cc per sec per atmosphere seems thus to be a good estimate of the intensity of the cosmic radiation at all points in the ionosphere.

If q ions are produced per cc per sec and the recombination-coefficient is α, the number of ions existing in equilibrium with the ionizing source is

$$n = \sqrt{(q/\alpha)} \tag{1}$$

In the case of several ionizing sources

$$n = \sqrt{(q_1 + q_2 + \cdots)}/\sqrt{\alpha} \tag{2}$$

Since (2) is not a linear function of the q's, each source of ionization does not contribute independently of the others to the equilibrium-concentration. We define the contribution of the cosmic radiation, n_{c-r}, as the ion-concentration which would exist if no other source of radiation were present. Since $q = Ip$ and $\alpha = \alpha_0 pT/T_0$, where I is the cosmic-ray intensity expressed as the number of ions produced per cc per sec in air at one atmosphere and absolute temperature T_0 and α_0 is the recombination-coefficient at a pressure of one atmosphere, it follows that

$$n_{c-r} = \sqrt{IT/\alpha_0 T_0} \tag{3}$$

Without taking into account the variations of temperature with elevation, and choosing the value of $\alpha_0 = 1.6 \times 10^{-6}$ as given by the theory for atomic oxygen-ions at the temperature of -60° C prevailing in the stratosphere, the ion-densities are those given in Table 1. Underlying the

Table 1--Ion-densities

Height, km	0	20	40	60	80	100
Cosmic-ray intensity, ions/cc/sec/atmosphere	2.7	290	300	300	300	300
Equilibrium-density of atomic oxygen-ions No./cc	1.3×10^3	1.3×10^4	1.4×10^4	1.4×10^4	1.4×10^4	1.4×10^4
Equivalent-density of electrons, No./cc	0.088	0.90	0.92	0.92	0.92	0.92

calculations is the assumption that free electrons unite with oxygen-atoms in a time which is short compared with the time of recombination of two ions of opposite charge. The validity of this assumption is well established by the eclipse observations of Kirby, Berkner, Gilliland, and Norton. The equivalent electron-densities, n_{elect}, operative in the reflection of radio waves are related to the ion-densities, n_{ion}, in the ratio of the mass of the electron to that of the oxygen-ion.

$$n_{elect} = n_{ion}\, m_e/m_{ion} = n_{ion} \times 0.34 \times 10^{-4} \tag{4}$$

The equivalent electron-densities are in the last row of the Table.

Since the critical frequencies of radio waves for which reflection takes place require electron-densities of the order of 10^5 per cc, it is concluded that the cosmic-ray contribution to the conductivity of the upper atmosphere is negligible compared with that from other sources.

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ULTRA-VIOLET SOLAR RADIATION AND ATMOSPHERIC OZONE

Edison Pettit

The measurement at the Mt. Wilson Observatory of the ratio of the intensity of sunlight at 0.32μ to that at λ 0.5μ with the thermoelectric ultra-violet solar radiometer is now in its eleventh year. The original gold and silver films are on the lens-plate surfaces that were put on in 1924. The same optical system has been used throughout the series and few changes have been made in mechanical details. The same methods of reduction have been used throughout the series. Figure 1 shows graphs of the monthly average and three months running means of the

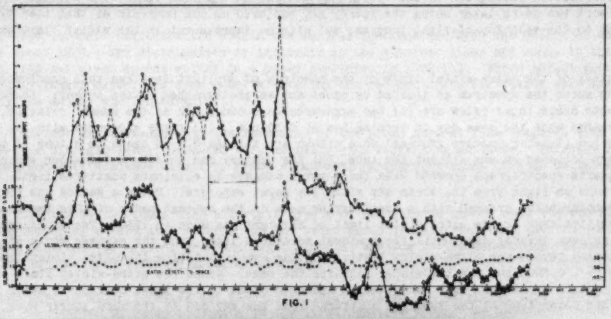
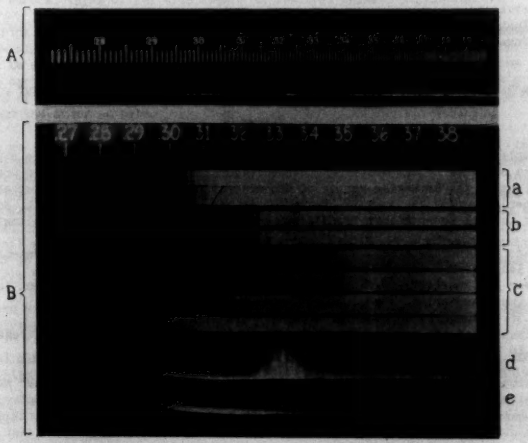


FIG. 1



ultra-violet (λ 0.32μ) to green (λ 0.5μ) ratio for no atmosphere and of the sunspot-groups observed on Mt. Wilson (dotted lines are monthly averages and full lines are three-month running means to smooth the curve). The unit is the average for June 1924. The maximum in the smoothed curve of 1.5 was reached in the autumn of 1925 and in the winter of 1926-27. Another high maximum of 1.4 was reached in January and February 1930. The minimum of 0.9 was continuous throughout almost the entire year 1932. The data here refer to 2730 days on Mt. Wilson. Below this curve is the monthly average "ratio zenith to space" which is the atmospheric transmission-coefficient for λ 0.32μ with reference to that for λ 0.5μ and above is the monthly average and three months running means of the daily number of sunspot-groups as observed at Mt. Wilson. Whether there is any evidence of a connection between the ultra-violet and sunspot-curves will probably depend on the events of the next cycle. Possibly the major variations in the ultra-violet curve are due in part, at least, to atmospheric ozone which is somewhat effective at λ 0.32μ.

That the ozone-absorption is effective in the lower atmosphere is known from photographs of spectra through long air-paths. About nine years ago Anderson and Babcock photographed the spectrum of the iron arc stationed on Mt. Wilson with a quartz spectrograph in Pasadena, a distance of 5.6 miles, as in Figure 2A (last lines visible in the violet are at λ 0.275μ). The furthest it was possible to photograph to the violet was the two strong iron lines at λ 0.275μ. I repeated this work two years later using the Sperry arc employed on the Mountain at that time by Michelson in the velocity-of-light program, but with no improvement in the violet limit obtainable.

A study of the ultra-violet limit of the spectrum of skylight confirms this conclusion. Figure 2B shows the spectrum as limited by ozone and as photographed by the author: Above is a wave-length scale in μ; below are (a) two exposures on noonday Sun at the summer solstice, (b) two exposures made the same day on evening Sun at 6:30 p.m., (c) three exposures with the same spectrograph (1-meter concave grating) on a carbon arc through 0.3-cm ozone in a tube in the laboratory followed by one without the tube, (d) the noonday Sun on July 1 (one-hour exposure) with a quartz spectrograph crossed with the 1-meter concave to eliminate scattered light, and (e) the same on light from the north sky with five days' exposure. Using a Bausch and Lomb quartz monochromator crossed with a spectrograph made of the optical parts of this instrument, a more sensitive test of the ultra-violet limit of skylight was made in 1930. The exposures were carried on over several days until the residual scattered light from the exposed strip of spectrum extended beyond the ultra-violet limit. For the summer solstice the ultra-violet limit was found to be λ 0.296μ and for the winter solstice the same. Since the ultra-violet limit of direct sunlight is λ 0.2897μ, this result would indicate ozone in the lower atmosphere which increases the absorption of the sunlight scattered from the sky due to its much longer path.

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THE AURORA AND NIGHT-SKY SPECTRA AND THE UPPER ATMOSPHERE--REPORT ON RECENT WORK

L. Vegard

Fairly complete accounts of the data relating to the auroral spectrum and the state of the upper atmosphere obtained by the writer and his collaborators up to 1933 have been published in a number of papers in the Norwegian series of Geophysical Publications [see references 1, 2, and 3 at end of paper]. During the last few years the writer, in collaboration with L. Harang and E. Tønsberg at the Auroral Observatory, Tromsø, has devoted much attention to the following problems:

(a) To find means for increasing the accuracy of our wave-length determinations especially in the region of long waves
(b) To make clear the intensity-variations within the auroral spectrum with respect to varying altitude, type, and color
(c) Comparison of the auroral spectrum with that of the night sky
(d) The determination of the temperature of the auroral region by means of the nitrogen-bands appearing in the auroral spectrum

(1) Precision-measurements in the region of long waves were made by the writer and L. Harang. An auroral spectrum in the infra-red region was obtained with a grating-spectrograph described in a previous paper [2]. The results were in good agreement with those previously obtained by prism-spectrographs of smaller dispersion, and they confirmed the view that the infra-red luminescence consists of bands belonging to the first positive group of nitrogen.

Using an interferometer-method similar to that used by Babcock for the night sky, we have taken a large number of interferometer-pictures of the green auroral line. A fairly complete account of the results of these measurements was recently published in the Norwegian Geophysical Publications. The wave-length found was λ = 5577.3445 ($\pm$0.0027). Within the limit of error this value coincides with that found by Babcock for the green line from the night sky and with the OI-line ($^1S_0$ - $^1D_2$) discovered by McLennan and his collaborators.

Interference-pictures taken in the direction of the streamers and perpendicular to them, gave the same wave-length. Thus the emitting centers have no noticeable motion in the direction of the streamers.

Recently our investigations were extended to the red line 6300. During an auroral display in January 1934 an interferometer-picture of the red line 6300 was obtained at the Auroral Observatory, Tromsö, with a Fabry-Perot quartz-etalon, 2.5 mm thick. A preliminary account of this result was given in a recent letter to "Nature." Our results show that the red line in question is an atomic line. The error of our spectrographic measurements being about $\pm$1 Å, there is a certain ambiguity as to the order-number of interference. It is, however, interesting to note that one of our values (6300.322), within the limit of error, coincides with the value (6300.328) derived from the electronic OI-states given by Hopfield.

(2) The intensity-distribution within the auroral spectrum has been the object of extensive studies since 1923. The distribution of intensity of the stronger lines and bands in the region 5600 to 3100 was given by the writer in a paper published in 1932 [1]. These investigations were extended to longer waves, and some results covering the red and infra-red region were given in a paper by the author and Tönsberg [6].

In 1923 the writer found that the intensity of the green auroral line compared with that of the negative nitrogen-bands decreased very markedly with increasing altitude. Recently L. Harang has confirmed this altitude-effect by means of auroral photographs taken through suitable filters [4].

In 1925 the writer found that a certain type A of red-colored aurora owed its red color to the enhancement of a line at λ = 6300. On the other hand, he suggested that the red lower edge sometimes observed for auroral arcs and bands (type B) was due to the enhancement of red bands belonging to the first positive group of nitrogen.

Some spectra which Tönsberg and the writer obtained from red aurora of type B have actually shown an enhancement of bands belonging to the first positive group. We have also found that the various auroral types differ with regard to spectral intensity-distribution.

(3) During the last two years Tönsberg and the writer have taken a large number of spectrograms of the night-sky luminescence both at Tromsö and Oslo. The main purpose of these investigations was to compare the type and intensity-distribution of the spectrum of the night sky with that of the aurorae. In order to obtain comparable spectra we tried, as far as possible, to obtain spectra of the night sky and of the aurora on the same plate, even when one had to be taken at Tromsö and the other at Oslo.

In the yellow and red region the spectrum of the night sky is dominated by the Green line (5577) and a few strong bands in red, which correspond to bands found in the auroral spectrum, although the positions of the maxima are somewhat different. In the night-sky luminescence, just as in the case of the aurorae, the intensity of the red line 6300 is subject to large variations. Sometimes it is too weak to be noticed, while at other times a maximum near 6300 is quite strong. This maximum is probably due to the OI-line ($^3P_2$ - $^1D_2$). The other red bands from the night sky belong to the first positive group, and appear with an intensity-distribution very similar to that shown by the spectrum from the afterglow of gaseous nitrogen. The band ($n' = 9 \rightarrow n'' = 5$) and the sequence ($n' - n'' = 2$) predominate.

Compared with the green line, the red bands of the night sky are 4 to 10 times stronger than the corresponding auroral bands.

Typical night-sky luminescence free from aurorae does not seem to contain bands of the second positive and the first negative group, which are very intense in the auroral spectrum.

These typical differences are indeed to be expected from the results previously obtained by the writer on the state of the upper atmosphere and the excitation-process underlaying the two luminescence-phenomena.

The aurorae are produced by the excitation of electric (probably electron) rays. The nitrogen band-spectrum which we observe from the aurora is essentially of the same type as that obtained when nitrogen at low pressure is exposed to cathode rays. The green and red OI-lines are produced indirectly through the action of activated nitrogen on O_2- or O_3-molecules.

The light of the night sky is a kind of afterglow resulting from the action of solar rays of short wave-length which during the daytime bring the upper atmosphere into the state of a terrestrial corona. In this coronal state, the atmospheric matter is highly ionized and activated. The light from the night sky results from the recombination-process taking place during the night.

(4) An estimate of the temperature of the auroral region by means of the negative bands was made by the writer as early as 1923. Quantitative measurements from spectra obtained during 1923-24 were published (Terr. Mag., v. 27, 389-398, 1932). As the rotational components do not appear separated, the temperature was found by comparing the auroral bands with the nitrogen-bands taken at known temperatures with about the same dispersion.

These investigations have been continued during later years. First of all we have continued our laboratory-experiments in order to test the accuracy of the method and to find out how far the apparent band-temperature is influenced by the excitation-process. The results were described in a paper recently published by the Norwegian Academy [9]. It was found that the distribution of rotational energy and the corresponding "band-temperature" were very little affected by excitation by swift cathode-rays, while canal-rays increased the band-temperature by about 90° C.

At the same time the writer in collaboration with Tønsberg has continued to take spectrograms of the auroral bands with a spectrograph of large dispersion. An intensity-scale was obtained by using a Zeiss "Stufenfilter" in front of the slit, and for a control a separate scale was obtained by taking spectra from a constant source with varying times of exposure. In 1933 and 1934 we obtained four spectrograms suitable for temperature-measurements. The results are given in a paper communicated to the Norwegian Academy.

The intensity-distribution within the bands indicates that considerable temperature-variation may occur in the auroral region. The most probable average value derived from our spectrograms was found to be 225°4 K or -47°6 C, which is somewhat lower than the temperature given in the first paper.

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[6] L. Vegard and E. Tønsberg, Die spektrale Intensitätsverteilung im Nachthimmellicht und Nordlicht, Zs. Physik, v. 88, pp. 709-726, 1934.
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[8] L. Vegard and E. Tønsberg, Continued investigations on the temperature of the upper atmosphere determined by means of bands appearing in the auroral spectrum, to appear in Geofys. Pub., v. 11, 1935.
[9] L. Vegard, On the determination of temperature by means of band-spectra, Norsk. Vid. Akad. Avh. I, No. 12, 1934.

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COSMIC-DATA URSIGRAMS

Watson Davis

AMERICAN CODE (AS OF APRIL 15, 1935)

Cooperating with the American Section of the International Scientific Radio Union, Science Service collects daily data on terrestrial magnetism, the solar constant, sunspots, and other phenomena, in order that they may be distributed by radio and other means to those interested.

The United States Navy by giving radio transmission to the daily cosmic-data message, the United States Army by transmitting by radio to Washington data from outlying points, the United States Coast and Geodetic Survey by furnishing magnetic data, the Mount Wilson Observatory of the Carnegie Institution of Washington by furnishing sunspot-data, the Astrophysical Observatory of the Smithsonian Institution by furnishing solar-constant values, the National Bureau of Standards by furnishing Kennelly-Heaviside layer heights, participate actively and fundamentally in the project.

Transmission-schedule--The Ursigrams in code described below are transmitted by radiotelegraphy, using International Morse Code, daily including Sunday from Navy radio station, NAA, Arlington, at 22:30 Greenwich time (5:30 p.m., Eastern Standard Time) on frequency of 9050 kilocycles at all times, plus the addition of 4525 kilocycles from November to March, inclusive.

Time used--Greenwich time, reckoned from midnight, is used in the Ursigrams. This is variously known as Greenwich Mean Time (G.M.T.), Greenwich Civil Time (G.C.T.), Universal Time, Weltzeit, etc. It is the time used by astronomers throughout the world since 1925 when they changed the astronomical day so that it begins at midnight instead of at noon. Noon or 12:00 Greenwich Time is 7 a.m. United States Eastern Standard Time, etc.

Code used--The letters URSI are the distinguishing sign at the beginning of the cosmic-data message. URSI are the initials of the Union Radio Scientifique Internationale (International Scientific Radio Union). Each class of data is coded separately and preceded by an identifying word, namely, RAD for solar constant, MAG for terrestrial magnetism, SOL for sunspots, AUR for aurorae, KHL for Kennelly-Heaviside layer heights. The data are expressed in a number code in groups of five, similar to that used in the transmission of meteorological information. Plain English will be added when extraordinary phenomena demand it. The message is signed SCIENSERVC, the cable address of Science Service. Unused figures are transmitted as X.

RAD (Solar constant)

First figure indicates day of week:
1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday
Second, third, and fourth figures:
Decimal fractional portion of solar-constant value; add one to obtain complete value. When 933 is transmitted, the solar constant is 1.933 calories. The solar constant of radiation is defined as the total intensity of solar radiation outside the Earth's atmosphere at the Earth's mean distance from the Sun and is expressed in calories per square centimeter per minute--the calorie, being the amount of heat required to warm one gram of water at 15° C through 1° C and the unit intensity of radiant intensity being defined as that which, if completely absorbed by a surface at right-angles to the beam, will produce one calorie of heat per square centimeter per minute.
Fifth figure indicates character of solar-constant value:
3 = Satisfactory 5 = Satisfactory minus (not quite satisfactory) 7 = Unsatisfactory
Example--RAD 79333 = Saturday, solar constant, 1.933 calories, satisfactory

Solar-constant data are supplied by the Astrophysical Observatory of the Smithsonian Institution and are the averaged values of the solar-constant determinations of that organization's observers at Montezuma, Chile.

MAG (Terrestrial magnetism)

First group--First figure indicates day of week:
1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday
Second figure:
3 = Quiet day 5 = Day of moderate disturbance 7 = Greatly disturbed day

Third figure:
3 = Day marked by bay, a disturbance lasting only an hour or so, with departure from normal curve in one direction only, as ⌒
5 = Day marked by rapid pulsations
7 = Day marked by long-period pulsations or oscillations
9 = Day marked by irregular oscillations
X = Not used
Fourth figure indicates that second group gives time of:
3 = Beginning of disturbance
5 = End of disturbance
7 = Beginning of disturbance--end given in third group
X = Not used
Fifth figure:
Unused and sent as X
Second group--Gives Greenwich time of beginning or ending of disturbance as indicated by fourth figure of the first group; if there is a beginning and end on the same day, a third group will give time of ending
First and second figures:
Hours, preceded by zero if less than ten
Third and fourth figures:
Minutes, preceded by zero if less than ten
Fifth figure:
Tenths of minutes, in the case of a sudden commencement of a disturbance; other times will be given to whole minutes only and X will be fifth figure
Third group--See explanation above
Example--MAG 1535X 0840X = Sunday, day of moderate disturbance marked by bay--disturbance ends 08:40 Greenwich time

Terrestrial magnetic data are supplied by the United States Coast and Geodetic Survey from its Observatory at Cheltenham, Maryland; period covered is for 24 hours preceding 13:00 Greenwich and local day of the week as given by the first figure of the first group. [Before January 1, 1934, data were from Observatory at Tucson, Arizona, covering 24 hours ending 14:00 G.M.T.]

SOL (Sunspots)

First figure indicates day of week:
1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday
Second and third figures indicate:
Number of groups of sunspots, preceded by zero if less than ten
Fourth and fifth figures indicate total number of sunspots--preceded by zero if less than ten
Example--SOL 10314 = Sunday, three groups of sunspots containing a total of 14 spots
[Wolf Number equals K (10 g plus s) where g is the number of groups, s the number of spots, and K a constant--for Mt. Wilson about 0.77; the Wolf Number of the example given above is about 34.]

Plain English descriptions of unusual solar phenomena will be added where necessary. Sunspot-data are furnished by the Mt. Wilson Observatory of the Carnegie Institution of Washington, Pasadena, California, from observations made at about 16:00 Greenwich time (8 a.m. Pacific Standard Time) or as soon thereafter as weather permits.

KHL (Kennelly-Heaviside Layer)

First group--First figure gives the place of observation:
3 = Washington, D. C. (National Bureau of Standards)
5 = Medford, Massachusetts (Tufts College)
Others to be announced
Second figure indicates day of week:
1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday
Third and fourth figures:
Hour of observation in Greenwich time
Fifth figure is given as X (with exception mentioned below)
Succeeding groups--First three figures:
Frequency, in kc/sec divided by 10
Fourth and fifth figures:
Would give the KHL height in km divided by 10

When the frequency is greater than 10,000 kc/sec, the X at the end of the first group would be replaced by the first digit of the frequency, that is, by a 1 for frequencies from 10,000 to 19,999; if, in a given set of observations, the frequency changed from a value below to a value above 10,000 kc/sec, it would be necessary to insert a new first group giving the place and time and to write KHL before this group to distinguish it from the groups giving frequency and height

Example--KHL 3417X 28518 28022 29019 30126
KHL 3508X 95021 98025 KHL 35081 00026 01026

These signify that, for observations made at Washington on Wednesday at about 5 p.m. Greenwich time, the frequencies and heights were those given at the left below, and for observations at the same place on Thursday, at about 8 a.m. Greenwich time, the values were those given at the right below:

2650 kc/sec	180 km	9500 kc/sec	210 km
2800	220	9800	250
2900	190	10,000	260
3010	260	10,100	260

This code should be useful in the reporting of critical frequencies, from which ionizations can readily be calculated. When values not close to a critical frequency are reported, large frequency separations may be used, and indicate that the relation of frequency to height is nearly linear between the points given.

AUR (Aurorae)

First group--First figure indicates day of week:
1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday

Second figure indicates character of day:
0 = No aurora 1 = Faint 3 = Moderate 5 = Strong 7 = Brilliant
9 = No observations or no observations possible on account of cloudiness

Third and fourth figures:
Number of hours during which aurora present--preceded by zero if number is less than 10

Fifth figure:
Cloudiness on scale of 0,1,2,.....9,X [0 indicates no clouds and X indicates completely overcast sky]

Second group--First figure indicates form:
0 = Homogeneous quiet arcs without ray-structure
1 = Homogeneous bands without ray-structure
2 = Pulsating arcs without ray-structure
3 = Diffuse luminous surfaces without ray-structure
4 = Pulsating surfaces without ray-structure
5 = Feeble glow without ray-structure
6 = Varied forms without ray-structure
7 = Flaming aurora
8 = Varied without ray-structure and flaming

Second figure indicates form:
0 = Arcs with ray-structure
1 = Bands with ray-structure
2 = Draperies with ray-structure
3 = Rays
4 = Corona
5 = Varied forms with ray-structure
6 = Flaming aurora
7 = Varied ray-structure and flaming

Third figure:
Maximum area covered on a scale 1 to 5

Fourth and fifth figures:
Average altitude in degrees

Third group--First, second, and third figures indicate general position of aurora, combinations being reckoned for included position in clockwise direction:
0 = South 2 = West 4 = North 6 = East 8 = Zenith
1 = Southwest 3 = Northwest 5 = Northeast 7 = Southeast 9 = Whole sky

Fourth and fifth figures:
Greenwich mean hour--preceded by zero if the hour is less than 10--of the observed greatest display in the 24 hours preceding the time of filing report

Example--AUR 15082 25355 57817 = Sunday, day of strong auroral disturbance, aurora present during 8 hours, sky two-tenths overcast, pulsating arcs without ray-structure and varied forms with ray-structure, covering at maximum three-fifths of the visible sky, average altitude 55°, from northeast to southeast to zenith, greatest display at 17:00 Greenwich time

The auroral data are supplied by the Alaska Agricultural College and School of Mines from its auroral observatory at College, Alaska.

Example of cosmic-data message

URSI RAD 79333 MAG 1535X 0840X SOL 10314 AUR 21011 0X110 34510
KHL 3417X 28514 29516 320XX 33034 35027 41276 45025 45042 ..... SCIENSERVC

Other distribution

Upon request, Science Service will transmit the cosmic-data message telegraphically over commercial channels, tolls collect. If desired, the numerals will be rendered into the following code to reduce tolls: 1 = a, 2 = d, 3 = g, 4 = k, 5 = m, 6 = n, 7 = s, 8 = t, 9 = u, 0 = w, X = x.

Science Service compiles weekly in mimeograph form the data of the daily cosmic-data messages and upon specific request distributes them by mail to those who can utilize or distribute the information further. The Journal of Terrestrial Magnetism and Atmospheric Electricity, published by the Johns Hopkins Press, Baltimore, Maryland, publishes summaries of the cosmic data.

Science Service also utilizes the information of the cosmic-data messages in the preparation of its service to newspapers in such a way that the public will be kept informed of the occurrence of notable changes in the phenomena reported and the possible effects upon earthly conditions.

Those interested in correlating the cosmic data with other phenomena and in studying the literature upon the fields affected by the cosmic data reported will be placed in communication with competent authorities upon application to Science Service.

JAPANESE CODE

Chairman H. Nagaoka of the National Committee on Radio Research of the National Research Council of Japan under date July 12, 1932, advised his Committee had arranged to collect the data for the use of the Ursigram and broadcast it beginning on September 8, 1932. The data are collected in cooperation with the Naval Experimental and Research Establishment, the Central Meteorological Observatory of Japan, the Tokyo Astronomical Observatory, and the Department of Communications, and Ursigrams are broadcast from the Tokyo Radio Station (JAP). The Ursigram is transmitted weekly, on Saturday at 13 G.M.T. on frequency 11980 kc/sec. It is also transmitted from JUA at 13:10 G.M.T. on 5770 kc/sec.

Code used--Each class of data is coded separately and preceded by an identifying word: SOL for sunspots, MAG for terrestrial magnetism, and KHL for Kennelly-Heaviside layer heights. The data are grouped weekly beginning on Thursday and are expressed in a number-code in groups of five. Plain English will be added when extraordinary phenomena demand it.

SOL (Sunspots)

The code for the sunspots is composed of seven groups of five figures; in each group the first figure indicates day of week:

1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday

Second and third figures:
Number of groups of sunspots--preceded by zero if less than 10
Fourth and fifth figures:
Total number of sunspots--preceded by zero if less than 10

Plain English descriptions of unusual solar phenomena will be added where necessary. Sunspot-data are furnished by the Tokyo Astronomical Observatory.

MAG (Terrestrial magnetism)

The code for terrestrial magnetism is composed of two groups of five figures.

First figure of first group indicates place of observation:
8 = Kakioka, Ibaraki prefecture, Japan, in longitude east 140° 11' 21" and latitude north 36° 13' 51" at height above sea-level 28.2 meters
Second and third figures of first group:
Date on which the information commences and it is always fixed on Thursday
Fourth and fifth figures of first group:
State of terrestrial magnetism on Thursday and Friday
First to fifth figures of second group:
State of terrestrial magnetism on Saturday, Sunday, Monday, Tuesday, and Wednesday, respectively

The meaning of these figures is:

0 = Calm
1 = Rather calm
2 = Slight disturbance
3 = Disturbance
4 = Storm of rather sudden commencement
5 = Storm of sudden commencement
6 = Remarkable storm of rather sudden commencement
7 = Remarkable storm of sudden commencement
8 = Storm of slow commencement
9 = Remarkable storm of slow commencement

KHL (Height of the Kennelly-Heaviside Layer)

The code for the Kennelly-Heaviside Layer consists of three groups of five figures.

First figure of first group indicates the place of observation:
7 = Tokyo
Second, third, fourth, and fifth figures of first group:
Observed frequency in kc/sec divided by 10
First figure of second group indicates day of week:
1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday
Second and third figures of second group:
Nearest Greenwich mean time
Fourth and fifth figures of second group:
Height of the first Kennelly-Heaviside E-Layer in km divided by 10
Third group indicates height of second layer:
Figures of this group have the same meaning as in the second group with an exception that the fourth and fifth figures indicate the height of the F-layer in km divided by 10

Example--SOL 50102 60105 70110 10104 20102 30103 4XXXX MAG 80100 02106 KHL 7C4C0 51519 51537 = Sunspots observed at the Tokyo Astronomical Observatory: Thursday, 1 group of 2 spots; Friday, 1 group of 5 spots; Saturday, 1 group of 10 spots; Sunday, 1 group of 4 spots; Monday, 1 group of 2 spots; Tuesday, 1 group of 3 spots; Wednesday, no observation. Terrestrial magnetism observed at Kakioka: Thursday, calm; Friday, calm; Saturday, calm; Sunday, slight disturbance; Monday, rather calm; Tuesday, calm; Wednesday, remarkable storm of rather sudden commencement. Kennelly-Heaviside Layer height observed at Tokyo for a frequency of 4000 kc/sec on Thursday at 15:00 G.M.T. were 190 km for first layer and 370 km for second layer.

FRENCH CODE

The code-plan for Ursigram transmissions prepared by French radio stations under the auspices of the French Committee for Scientific Radiotelegraphy in force after January 1, 1932, replaced the Geophysical Bulletins previously transmitted in plain language by the radio stations Bordeaux and Pontoise, as well as the radiotelephonic station at the Eiffel Tower. The radiotelephonic station at the Eiffel Tower (207.6 kc/sec or 1445 meters) will continue to send out the geophysical and astrophysical bulletin in plain language. In addition to the Ursigram, the radiotelegraph stations of Lafayette (15.87 kc/sec or 18,900 meters) and Pontoise (10,526 kc/sec or 28.5 meters) will send out daily a series of letters for scientific studies of radiopropagation.

The following program in Greenwich mean time will be adopted for these various transmissions:

20:08, end of time-signal emission.
20:10 to 20:15, signals for propagation-study; emission of the letter é (....) and of a group of reference-letters
20:15, Ursigram

Ursigrams sent out by stations Lafayette and Pontoise will comprise:

(1) A very condensed meteorological bulletin, prepared by the National Meteorological Office
(2) A geophysical bulletin giving particulars of the state of the Earth's magnetism and the electrical state of the atmosphere, as prepared by the Physical Institute of the Globe (Institut de Physique du Globe) from observations made at the Observatory of Val Joyeux (Seine-et-Oise)
(3) An astrophysical bulletin, relating to solar activity, as manifested by observations of spots, protuberances, filaments (protuberances viewed sideways), and faculae, prepared from observations made at the Observatory of Meudon.
(4) A bulletin indicating centers of production of atmospherics, prepared from daily observations at 13:00 G.M.T. of the Radio Research Station at Slough (England), is to be sent out once each week--ordinarily on Mondays--and will give the centers as observed during the preceding week

(5) A bulletin indicating, for a given frequency, the height of the Kennelly-Heaviside layer, from measurements made by Professor Appleton, and forwarded by the British National Committee

The general scheme of Ursigrams will be as follows:

URSI URSI URSI BAR (text of the meteorological bulletin) MAG (text of the magnetic bulletin) ELC (text of the bulletin on atmospheric electricity) SOL (text of the bulletin on solar phenomena) ATS (text of the bulletin on atmospherics) KHL (text of the bulletin on the height of the Kennelly-Heaviside layer)

The codes for these different bulletins, except that for the meteorological bulletin BAR, are given below.

Code for magnetic phenomena (MAG)

The magnetic Ursigram contains two groups of five digits each, here designated symbolically by the five-letter groups abcde and fghij.

a = day of week — 1 = Sunday 2 = Monday 3 = Tuesday 4 = Wednesday 5 = Thursday 6 = Friday 7 = Saturday

b = magnetic character of day from average of three magnetic elements — 0 absolute calm; 1 nearly calm; 2 slightly agitated; 3 agitated; 4 very agitated; 5 moderate storm; 6 strong storm; 7 very strong storm; 9 no observations made

c = details remarked on recorded curves
1, 2, 3, and 4 concerning declination (or Y) — 1 or 5 a single notch; 2 or 6 rapid pulsations; 3 or 7 long periods or swings
5, 6, 7, and 8 concerning horizontal component (or X) — 4 or 8 irregular oscillations
the more characteristic of the two elements Y and X will be selected — 0 = characterless day; 9 = no observations made

(Note--When several phenomena present themselves on the same day's record, such as notches, rapid pulsations, etc., that which seems the most important will be selected.)

d e = hours
f g = minutes
time of the commencement of the phenomenon

Note--In the case of a phenomenon having started the preceding day, it will be noted that
d = 8 e = 8 f = 8 g = 8
If no observation has been made, it will be noted that
d = 9 e = 9 f = 9 g = 9
The notation 9999 will also be used when the records show no disturbance, and in general when the outset of a disturbance is obscure

h = sharpness of onset — 1 = sudden onset; 2 = onset vague; 3 = no visible onset; time of onset unassignable; 8 = onset taken place on preceding day; 9 = no observation made--the same notation as when the record shows no disturbance

i j = hour (approximate) of the end of a phenomenon (counting 0 to 24)

Example: i j = 05 = ended about 5 o'clock; i j = 88 = when the phenomenon does not seem to have ended in the day specified; i j = 99 = no determination made; 99 will also be used when the record shows no perturbation and also when the termination is indefinite

Code for electric phenomena (ELC)

The atmospheric-electric Ursigram comprises a group of five digits, symbolized by a $b_1\ b_2\ c_1 c_2$.

Group a b_1 b_2 c_1 c_2

a = week day	1 = Sunday 2 = Monday 3 = Tuesday 4 = Wednesday 5 = Thursday 6 = Friday 7 = Saturday
b_1 = character of electric field from 0 to 12 hr	1 = nearly calm 9 = no observation made 2 = slightly agitated 3 = agitated 4 = very agitated (frequent changes from positive to 5 = inverted negative)
b_2 = character of electric field from 12 to 24 hr	1 = nearly calm 9 = no observation made 2 = slightly agitated 3 = agitated 4 = very agitated (frequent changes from positive to 5 = inverted negative)
c_1 = gradient of potential from 0 to 12 hr	1 = feeble 9 = no observation made 2 = medium 3 = strong 4 = very strong 5 = variable 6 = very variable
c_2 = gradient of potential from 12 to 24 hr	1 = feeble 9 = no observation made 2 = medium 3 = strong 4 = very strong 5 = variable 6 = very variable

Example--ELC 74386 is decoded thus: a = 7 = Saturday; b_1 = 4 = field very agitated from 0 hr to 12 hr; b_2 = 3 = field agitated from 12 hr to 24 hr; c_1 = 6 = gradient of potential very variable from 0 hr to 12 hr; c_2 = 6 = gradient of potential very variable from 12 hr to 24 hr

Code for daily message on solar activity (SOL)

This message comprises a group of five digits giving general indications as to the principal characters of solar activity. When the spots or protuberances are observed to be of more than usual importance, additional five-figure groups give the positions of these objects. It will be completed later by a description in plain language of the exceptional eruptive phenomena. The data are secured from observations made with the spectroheliograph of Meudon Observatory.

First group of general indications--First digit indicates day of week:

1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday

Second digit indicates activity expressed according to the number and importance of the spots, to scale 0 to 5:

0 = no activity 2 = medium 4 = strong
1 = feeble 3 = fairly strong 5 = very strong

Third digit indicates activity on scale 0 to 5 of number and extent of bright areas with calcium- and hydrogen-faculae

Fourth digit indicates activity on scale 0 to 5 of number and importance of protuberances projected against the solar disc (filaments)

Fifth digit indicates activity on scale 0 to 5 of number and importance of protuberances observed externally, on the edge

Supplementary groups--First digits of three supplementary groups (a), (b), and (c) identify phenomenon whose position is to be stated, namely, (a) 3 for spots, (b) 5 for filamentary protuberances on disc, (c) 7 for protuberances on edge

Second digit of group (a) is quadrant of Sun's disc on which spot, or the center of a group of spots, is found:

2 = north-east quadrant 4 = south-east quadrant 6 = south-west quadrant
8 = north-west quadrant

[Note--The quadrants are demarcated by the central meridian passing through the poles of the Sun, and by the perpendicular to this meridian passing through the center of the disc.]

Third digit of group (a) is distance from the spot to the central meridian, expressed in days

Fourth and fifth digits of group (a) are same as 2 and 3, respectively

[Note--If the number of spots to be specified exceeds two, additional five-figure groups, commencing with the digit 3, and particularized as above, will be inserted; this is, however, unlikely, and more than four spots are never specified, in one message. When there are an odd number of spots, the fourth and fifth digits of last group will be replaced by X.]

Second digit of group (b) is quadrant of the disc on which middle of filament appears, according to notation for spots

Third digit of group (b) is distance from the middle of the filament to the central meridian, expressed in days

Fourth digit of group (b) indicates latitude of the filament (unnecessary for spots which are always in low or mean latitude):

4 = filament of low or of medium latitude 6 = filament of polar latitude

Fifth digit of group (b) is not used and is replaced by an X

[Note--There will be transmitted as many five-digit groups commencing with 5 as there are filaments to specify; their number will probably never exceed three.]

Second digit of group (c) is quadrant containing the middle of the protuberance, as per notation for spots

Third digit of group (c) indicates position of the protuberance in latitude:

Notation same as fourth digit of group (b)

Fourth and fifth digits of group (c) are same as its second and third digits, respectively

[Note--If the number of protuberances to be specified exceeds two, extra five-digit groups will be added, commencing with 7, and particularized as above. These cases rarely occur. When there are odd numbers of protuberances to be specified, the fourth and fifth digits of the last group will be replaced by X.]

Examples--(1) Message on observations of Sunday, November 23, 1930, reading SOL 14312 34144 584XX is decoded thus: Sunday sunspot-activity strong; in facula areas of calcium and hydrogen, fairly strong; in filaments, feeble; in edge-protuberances, medium; three important spots, one in south-east quadrant and 1 day from meridian, one in south-east quadrant and 4 days from meridian, one in north-west quadrant and 4 days from meridian.

(2) Message on observations of Thursday, July 19, 1928, reading SOL 52440 362XX 5224X is decoded thus: Thursday sunspot-activity medium; in faculae strong; in filaments strong; in edge-protuberances, nul; important group of spots is to be noted in the south-west quadrant and 2 days from the central meridian; an important filament is in the north-east quadrant and 2 days from the central meridian and of low or medium latitude.

(3) Message on observations of Thursday, November 7, 1929, reading SOL 53434 34284 5804X 74684 is decoded thus: Thursday sunspot-activity fairly strong; in faculae strong; in filaments fairly strong; in edge-protuberances strong; two important spots or spot-groups are reported, one in south-east quadrant and 2 days from central meridian, one in north-west quadrant and 4 days from central meridian; an important filament is found in the north-west quadrant, at least 0.5 day from central meridian in medium or low latitude; two important protuberances are reported, one in south-east quadrant, polar, and one in north-west, low or mean latitude.

Code for centers of production of atmospherics (ATS)

There will be transmitted on each reported day, one three-group series of five-digit groups for each reported center of disturbance sources. Each series will be of the following type: JJC LLLQI IIiii.

First group:

JJ = day of month for observation

C = character of center of disturbance, being 1 for a large zone (sources distributed over a radius of 200 km around the position indicated) and 3 for a small zone (sources contained within a well-defined region of 50-km radius)

Second group:

LLL = latitude, in degrees and tenths of a degree

Q = octant of globe, being (in the Northern Hemisphere) 0 for longitude 0° to 90° west of Greenwich, 1 for longitude 90° to 180° west of Greenwich, 2 for longitude 180° to 90° east of Greenwich, 3 for longitude 90° to 0° east of Greenwich; the digit 4 will be added to the Q number for a source in the Southern Hemisphere

Third group:

II = longitude in degrees and tenths of a degree

iii = integrated intensity in millivolts per meter per minute for those of the observed atmospherics whose individual values exceed 5 millivolts per meter, individual values of less than 5 millivolts per meter being neglected

Only the centers of most marked disturbance will be reported each day.

Example--Message for date of August 24 (13 hr G.M.T.) reading ATS 241 40005 50126 243 35005 30041 is decoded thus: On August 24 a large zone latitude 40°0 north in quadrant 0° to 90° west and longitude 55°0 integrated intensity 126 millivolts per meter and per minute; a small zone latitude 35°0 in quadrant 0° to 90° west and longitude 53°0 of intensity 41 millivolts per meter and per minute.

Height of the Kennelly-Heaviside layer (KHL)

This Ursigram will comprise two five-digit groups.

First group--First digit indicates locality in which measurement was made
1 = London 3 = Washington
[Note--The American National Committee has adopted the digit 3 to indicate Washington; it is believed that the digit 1 should be assigned to London, Professor Appleton having been the first to carry out measurements of layer-heights.]
The last four digits indicate wave-frequency employed in tens of kc/sec
Second group--First digit indicates day of week:
1 = Sunday 3 = Tuesday 5 = Thursday 7 = Saturday
2 = Monday 4 = Wednesday 6 = Friday
Second and third digits indicate nearest hour of Greenwich mean time
Fourth and fifth digits indicate the height of the layer in tens of kilometers

In cases where a second layer is indicated by the measurements, the height of the latter would call for an additional five-digit group.

Example--Message KHL 11252 20812 is decoded thus: At London, for a frequency of 12520 kc/sec, on Monday at 8 o'clock G.M.T., the height of the layer was found to be 120 km.

Science Service,
Washington, D. C.

RESOLUTIONS ADOPTED

(I) RESOLUTION ON THE PROPOSED CONSTRUCTION BY GREAT BRITAIN OF A MAGNETIC-SURVEY VESSEL

WHEREAS, The magnetic survey of the oceanic areas, carried on for 25 years by the Carnegie Institution of Washington, was brought to a sudden end by the destruction of the Carnegie at Apia, Western Samoa, November 29, 1929, in the course of a cruise designed to determine the secular change of the Earth's magnetism in all oceans, and

WHEREAS, It is of very great importance, not only for the practical needs of the navigator but also for the effective study of the Earth's magnetism, that these observations be resumed at an early day, and

WHEREAS, It has been announced that the British Admiralty has decided to build a non-magnetic vessel, designed primarily for securing magnetic data at sea, therefore be it

RESOLVED, That the American Geophysical Union is highly gratified at this action of the British Government, assuring, as it does, the continuance of the ocean magnetic work, and expresses the hope that the construction and equipment of the vessel may be pushed to a speedy conclusion, and be it further

RESOLVED, That a copy of this resolution be sent to the British Admiralty, to the Astronomer Royal, and to the Chairman of the British National Committee for Geodesy and Geophysics.

(II) RESOLUTION ON SUITABLE VESSEL IN UNITED STATES NAVY FOR OCEANIC SURVEYS

WHEREAS, There is a great need for a continuation of the magnetic survey initiated by the Carnegie Institution of Washington and brought to an untimely end by the destruction of the Carnegie, leaving serious gaps in our present knowledge of the magnetic variations at sea, and

WHEREAS, The secular variations in the Indian Ocean and no doubt in other areas are changing so rapidly as to render extrapolated values unreliable, be it

RESOLVED, That the American Geophysical Union recommend and urge the United States Navy to take steps to build a suitable vessel for the gathering of magnetic, atmospheric-electric, and oceanographic data, thus cooperating in advancing the work to be done by the non-magnetic vessel being constructed by the British Admiralty, and be it further

RESOLVED, That a copy of this resolution be sent to the Secretary of the United States Navy Department and to the Hydrographer.

(III) RESOLUTION ON BATHYMETRIC CHARTS OFF WEST COAST OF UNITED STATES

WHEREAS, There has been completed recently in great detail some interesting surveys off the west coast of the United States, be it

RESOLVED, That the American Geophysical Union request the proper governmental bureau or agency to prepare bathymetric charts of the topography of the sea-floor in these regions.

(IV) RESOLUTION ON MAKING AVAILABLE FOR SCIENTIFIC USE ACCUMULATED GEOLOGICAL AND GEOPHYSICAL DATA OBTAINED BY UNITED STATES COAST AND GEODETIC SURVEY AND NAVY DEPARTMENT

WHEREAS, There has been accumulated a vast fund of information by the United States Coast and Geodetic Survey and the Hydrographic Office of the United States Navy, much of which bears directly on geological and geophysical problems, be it

RESOLVED, That the American Geophysical Union bring to the attention of the heads of these bureaus the desirability of making this information available to its fullest extent for the use of science.

(V) RESOLUTION ON ESTABLISHMENT OF MOUNTAIN STATIONS AND USE OF RADIO METEOROGRAPHS

WHEREAS, It has been demonstrated that free-air data are immediately obtainable both in foggy and in stormy weather by mountain stations and by radio sounding balloons when meteorological airplane-flights are too hazardous, and

WHEREAS, The use of radio meteorographs on airplanes would make the data immediately available, therefore be it

RESOLVED, That the American Geophysical Union (1) urge that the Weather Bureau be given the necessary funds for the development of its program for mountain meteorological stations in the United States and for the use of radio meteorographs on airplanes and on balloons, (2) commend the

pioneer efforts of the Blue Hill Observatory of Harvard University (a) in helping to establish and, with the aid of the Rockefeller Foundation and private contributions, continuing to operate the Mt. Washington Observatory, and (b) in devising experimental radio meteorographs with ultra-high-frequency transmitters, direction-finders, and recording receivers of light weight and low cost, and hope that means may be found for continuing these activities, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of Agriculture, the Director of the Bureau of the Budget, the President of the Rockefeller Foundation, and the President of Harvard University.

(VI) RESOLUTION ON ENCOURAGING DESIGN AND MANUFACTURE OF RADIO METEOROGRAPHS

WHEREAS, Observations of temperature, pressure, and humidity in the free-air are essential to the analysis of air-masses, and

WHEREAS, Owing to adverse weather-conditions, it is impracticable at times to obtain such information by means of airplanes, and

WHEREAS, An instrument has been devised to be carried by a balloon whereby such data can be transmitted by radio to an observer on the ground, therefore be it

RESOLVED, That designers and manufacturers be encouraged to improve such apparatus so that in the event of failure of ascents by airplane the radio apparatus could be employed with a small balloon to obtain the necessary free-air data.

(VII) RESOLUTION ON SEISMOGRAPH-STATION AT CARLETON COLLEGE

WHEREAS, The installation of a seismograph-station is contemplated at Carleton College, Northfield, Minnesota, and

WHEREAS, The addition of this station would aid in filling an important gap in the network of such stations in the United States, be it

RESOLVED, That the American Geophysical Union endorse this project and express the hope that means may be found to carry it into execution, and be it further

RESOLVED, That copies of this resolution be sent to the President of Carleton College, to Professor E. A. Fath, sponsor of the project, of that institution, and to the Director of the United States Coast and Geodetic Survey.

(VIII) RESOLUTION ON SEISMOGRAPH-STATION AT NEBRASKA WESLEYAN UNIVERSITY

WHEREAS, The installation of a seismograph-station is contemplated at Nebraska Wesleyan University, Lincoln, Nebraska, and

WHEREAS, The addition of this station would aid in filling an important gap in the network of such stations in the United States, be it

RESOLVED, That the American Geophysical Union endorse the project and express the hope that means may be found to carry it into execution, and be it further

RESOLVED, That copies of this resolution be sent to the President of Nebraska Wesleyan University, to Professor J. C. Jensen of that institution, the sponsor of the project, and to the Director of the United States Coast and Geodetic Survey

(IX) RESOLUTION ON SEISMOGRAPH-STATION AT WEST BADEN COLLEGE

WHEREAS, The installation of a seismograph-station is contemplated at West Baden College, West Baden, Indiana, and

WHEREAS, The addition of this station would aid in filling an important gap in the network of such stations in the United States, be it

RESOLVED, That the American Geophysical Union endorse this project and express the hope that means may be found to carry it into execution, and be it further

RESOLVED, That copies of this resolution be sent to the President of West Baden College, to the President of Xavier University, Cincinnati, Ohio, to the President of the Jesuit Seismological Association, and to V. C. Stechschulte, S.J., of Xavier University.

(X) RESOLUTION ON COORDINATED PLAN OF SNOW-SURVEYS IN MOUNTAIN REGIONS

WHEREAS, The irrigation water-supply in western states is determined to a great extent by the winter snowfall, and

WHEREAS, The value of snow-surveys has been demonstrated, but coordinated plans for snow-surveying and predicting stream-flows from the resulting data have not been made, and

WHEREAS, Reliable forecasts of stream-runoff prior to the flood-flow season would afford warning of impending floods and of water shortages, thus making possible effective measures against flood-damage and adjustment of agricultural programs to meet water shortages, therefore be it

RESOLVED, That the Secretary of Agriculture, in cooperation with appropriate agencies, be requested to authorized and to undertake a coordinated plan of snow-surveys in mountain regions where conservation of water by natural and artificial storage is economically important, together with necessary studies of methods and equipment, and be it further

RESOLVED, That the American Geophysical Union, through its Section of Hydrology, offer its full cooperation and services in the formulation of such a plan.

(XI) RESOLUTION ON PERMANENT AGENCY TO DIRECT AND COORDINATE WORK IN HYDROLOGY BY FEDERAL GOVERNMENT

WHEREAS, The important work in hydrology now being carried out by the several bureaus and other agencies of the Federal Government loses much of its usefulness through lack of coordination and lack of adequate means for prompt publication and availability to the public, therefore be it

RESOLVED, That a permanent agency should be provided to direct and coordinate the work of these various bureaus and other agencies in the collection and dissemination of hydrologic data, and, further, that arrangements be made for full, prompt, and adequate publication of such data.

(XII) RESOLUTION ON COLLECTION OF GROUND-WATER LEVEL DATA IN THE UNITED STATES

WHEREAS, The recent western drought has demonstrated the practical value of ground-water level records, and

WHEREAS, Such records are now kept only in certain localities and no general means of publication of the results is now available, and

WHEREAS, Such records are of value not only in relation to water-supply and agriculture but also these results are often of direct scientific value in interpreting the phenomena of the hydrologic cycle, be it

RESOLVED, That the Secretary of the Interior be requested to make provision for the collection of ground-water level data in accordance with a complete and comprehensive plan, covering the entire United States, and that provision be made for prompt and full publication of the data and results.

(XIII) RESOLUTION ON A MANUAL ON HYDROLOGY

WHEREAS, The science of hydrology is of increasingly great importance in practical application to national problems of water-sources, and

WHEREAS, There is a great need for an authentic source-manual on scientific hydrology similar to the manuals provided for or already published in the series "Physics of the Earth," therefore be it

RESOLVED, That the American Geophysical Union recommend to the National Research Council that a volume on Hydrology be added to the series on "Physics of the Earth" and that a subsidiary committee on hydrology be appointed to prepare matter for such a volume.

(XIV) RESOLUTION ON DEATH OF EDWARD M. BURD

WHEREAS, In the death of Edward M. Burd in an airplane accident during November 1934, the American Geophysical Union has lost a member who has long been active in hydrological studies, and

WHEREAS, Mr. Burd has been actively engaged in coordinating the ideas of many investigators on the subject of stream-flow prediction, therefore be it

RESOLVED, That the American Geophysical Union express its sense of great loss through his untimely death, and be it further

RESOLVED, That a copy of this resolution be sent to Mr. Burd's family.

(XV) RESOLUTION ON DEATH OF GEORGE LEONARD HOSMER

WHEREAS, In the death of George Leonard Hosmer on January 10, 1935, the American Geophysical Union has lost a member who has long been active in the fields of geodesy and seismology, and

WHEREAS, Professor Hosmer has distinguished himself as a teacher of geodetic surveying, and as an author and engineer who has made notable contributions to the literature and technique of that branch of engineering, and

WHEREAS, Professor Hosmer was active in the establishment of a seismograph station at Technology, the summer surveying camp of the Massachusetts Institute of Technology, near East Machias, Maine, which station is making notable contributions to the sciences of seismology and geodesy, therefore be it

RESOLVED, That the American Geophysical Union express its sens of great loss through the death of this great teacher, scientist, and engineer, and be it further

RESOLVED, That copies of this resolution be sent to Mrs. Hosmer and to the President of the Massachusetts Institute of Technology.

(XVI) RESOLUTION ON THE DEATH OF WILBUR GARLAND FOYE

WHEREAS, In the death of Wilbur Garland Foye on January 8, 1935, the American Geophysical Union has lost an active worker in the field of the petrology of igneous and metamorphic rocks, and

WHEREAS, He made notable contributions to the mineralogy, petrology, and structure of the New England region, as well as to the age of intrusive rocks by radioactive methods, therefore be it

RESOLVED, That the American Geophysical Union express its sense of great loss through his death, and be it further

RESOLVED, That a copy of this resolution be sent to Professor Foye's family.

(XVII) RESOLUTION ON DEATH OF DAVID WHITE

WHEREAS, The American Geophysical Union has learned with deep regret of the death on February 7, 1935, of David White, special scientist in the United States Geological Survey and a member of the Survey since 1886, and

WHEREAS, Dr. White has been constantly associated with the National Research Council since 1919, serving as Chairman of its Division of Geology and Geography from 1924 to 1927, and as a member of various committees of the Division, and

WHEREAS, Through his numerous outstanding and authoritative contributions to geophysics, he rendered an important service in furthering the purposses for which the American Geophysical Union was established, therefore be it

RESOLVED, That the American Geophysical Union record its recognition of the especially meritorious services of Dr. White in advancing the science of geology and in stimulating research in other fields of Earth science as well, and be it further

RESOLVED, That a copy of this resolution be sent to Dr. White's family.

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AMERICAN GEOPHYSICAL UNION

Sixteenth Annual Meeting

SECTION OF GEODESY

Washington, D. C.
April 25, 1935

Reports and papers

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SCIENTIFIC NEEDS FOR ACCURATE TIME-SERVICE

Lyman J. Briggs

Many important lines of investigation involve the accurate measurement of time and the overall precision of the work may in fact rest upon the precision with which measurement of time can be carried out. Examples are to be found in the determination of longitude, in the measurement of the rate of propagation of seismic disturbances, and in isostatic problems involving a precise determination of the acceleration of gravity at various points over the Earth's surface. To these examples may be added the many uses of time by the physicist, which broadly speaking center around the measurement of frequencies, velocities, and accelerations.

Nor are the requirements for a precise time-service limited by any means to the scientific fields which I have mentioned. The use of the gravity pendulum in searching for salt-domes and ore-bodies is a striking example of the utilization of refined time-measurements for very practical purposes. The same is true of the detonation-method used in geophysical prospecting, in which a charge of explosives buried in the ground is made to generate a compression-wave in the Earth, and the time required for this wave to reach some distant point is measured along with that of its slower air-borne companion. Other examples are to be found in the advances made by electrical power companies in operating their great generators day in and day out at a speed that so closely approximates sixty cycles a second that tiny synchronous motors may be used for clocks; and in the ability of broadcasting companies to maintain their carrier-wave frequencies well within the federal limits of approximately 0.005 per cent.

More precise measurements of time are necessary in the field of sports. In the hundred-yard dash the time is usually measured to only one-fifth of a second, yet the runners actually travel more than six feet in one-fifth of a second. Time measurements to 0.01 second are required.

In the automobile speed-trials at Daytona Beach speeds of over 276 miles per hour or 4.6 miles per minute have been attained. Since the time required to traverse the one-mile course is less than 13 seconds, the time must be measured at least to 0.01 second. In these contests a printing chronograph is used to measure the time, similar to that formerly employed by the Naval Observatory in recording star-transits. An error of 0.01 second in the measured time is equivalent to an uncertainty of four feet in the length of the one-mile course, or 0.2 mile per hour in the speed. Yet the speed is often given to three decimal places.

Two types of time-service are now available in this country to those who need to make accurate time-measurements. The primary and indispensable service is that rendered by the Naval Observatory to science and industry in maintaining the unit of time and in the broadcasting of signals which precisely limit certain time-intervals. Supplementing this service, and dependent upon it, is the standard-frequency service provided by the National Bureau of Standards. The first service may be characterized by epoch, time in the numerator; the second by rate, time in the denominator. Both services are made widely available through radio broadcasts. The Naval Observatory sends out twenty hourly signals each day on NAA (113 kc/s), supplemented by other signals on short wave-lengths. The Bureau of Standards at present broadcasts continuous signals for three hours two days a week. We hope that eventually this service may be greatly extended.

A brief presentation of the ways in which the frequency service supplements that given by the Naval Observatory may be of interest. I understand that the work of the Naval Observatory is so excellent that the maximum deviation of the signals from absolute exactitude in indicating the daily epoch is of the order of 0.01 second while the average error is only a few thousandths of a second. An error of 0.01 second in defining a twenty-four hour epoch represents a precision of one in 10,000,000, or in the case of the hourly signals of one in 500,000. If the observer in the laboratory could adapt his time-observations to periods covered by these high-precision signals the measurement of time would no longer give him concern. But his time-measurements often deal with much shorter periods in which an uncertainty of 0.01 second would not be permissible. Hence he must needs have recourse to other devices which have been calibrated by means of the standard time-signals. In such measurements the standard frequency service provided by the National Bureau of Standards finds wide application. The frequency-standard is maintained by means of six quartz-oscillators. The frequency is accurate to one part in 10,000,000 and is held constant during the emissions to one part in 100,000,000, or better

As a matter of fact, physical measurements involving time are largely concerned with the determination of rates such as frequency ($1/t$), velocity (s/t), and acceleration (s/t^2). Now it is generally far simpler to determine a frequency by comparing it with a standard frequency--if the latter is available--than to attempt to make a direct measurement of the time involved. In

fact a direct comparison with a standard of frequency is one of the simplest and most precise of all physical measurements. Consider, for example, the determination of the frequency of a tuning-fork which is found to give a beat note of one per second when compared with a standard 500-cycle fork. It follows at once that the frequency of the unknown fork differs from that of the standard fork by one cycle per second. To maintain the assigned frequency of a broadcast station its carrier-frequency is changed slowly until the beat-note formed with the frequency-standard disappears, at which time the carrier-frequency is precisely the same as the standard frequency with which it is being compared.

The standard-frequency signals thus provide directly a standard against which other frequencies may be measured by extremely simple beat-methods to an accuracy of a part in ten million. They also provide a means for measuring short-time intervals with high precision. Any desired frequency, produced in the receiving equipment by harmonic multiplication or demultiplication methods, may be used to control an ordinary electric clock equipped with a synchronous motor and to operate contacts on a chronograph. This can be done directly if the standard-frequency signals are sufficiently strong. The value of the service is such that it seems desirable that it be extended so that all places in the country can be reliably served at all times. Meanwhile, the service may be used, at such times as it is available, to calibrate a locally maintained oscillator which in turn controls the measuring equipment. Piezoelectric oscillators with a constancy requisite for scientific needs are available commercially. Magnetostriction apparatus and tuning-fork and other oscillators for less exacting work are also available. The use of the standard-frequency signals to calibrate the oscillators has the advantage that instantaneous variations of their rate can be determined. This cannot be done by the use of the epoch time-signals, which are adapted only to determining the average rate over a relatively long period.

Other illustrations of the ways in which scientific needs are served by these signals may be given from experience in various sections of the Bureau. Through the use of submultiple generators and synchronous motors, any desired frequency may be produced from the Bureau's standard of frequency. With the present equipment, frequencies ranging from radio frequencies down to 10 cycles per second are available; and through the use of contacts on the shaft of a synchronous motor, pulses are produced every second, once in five seconds, and once in ten seconds. These pulses are used for timing alpha-particle production-rates, battery-discharge rates, etc., and for determining the rate of the Shortt clock used in the absolute measurement of the acceleration of gravity.

Frequencies of 60 to 1000 cycles per second from the Bureau's standard are used for the following purposes: To control the rotation speed of standard generators for electrical instrument testing and for the absolute measurement of the ohm; to drive synchronous-motor counters which measure time-intervals for determining the speed of travel of velocity-meters in a tank; to calibrate tuning-forks and to stabilize an electrically-driven elinvar tuning-fork; to determine (by the aid of an oscillograph) the rate of a pendulum used in sound measurements; to supply a standard frequency for electrical bridge-methods of measurement. These are all measurements with exacting requirements of accuracy.

The Bureau's standard of frequency is used also for many purposes by others. One radio laboratory uses a 10-kilocycle frequency from the Bureau's standard as its standard of comparison in making commercial measurements on the frequencies of received radio stations; this is a specially convenient frequency, being the greatest common divisor of all broadcast-station frequencies. Other radio laboratories, transmitting stations, the inspection force of the Federal Communications Commission, etc., use the standard-frequency radio emissions as standards for radio work. A start is being made in providing standard audio frequencies as a modulation on the radio emissions. This will facilitate the work of those whose immediate need is for a standard of audio frequency. One laboratory reports great satisfaction in the use of a standard frequency of 1000 cycles per second (transmitted by the Bureau as a modulation in some experimental radio-emissions) for calibration of tuning-forks, using an oscillograph for the intercomparison.

The use of a standard audio frequency as a modulation on the standard-frequency radio emissions will provide very conveniently for such time-rate needs as those of jewelers and some systems of television synchronization. It is believed also that such a frequency may be of material advantage to electric power-companies in the accurate control of frequencies of 60-cycles per second. The general availability of a convenient frequency through radio dissemination may simplify the work of the power-companies, both in maintaining a uniform frequency for the operation of electric clocks and in facilitating the shift of load-control among interconnected systems. All of these applications of audio frequencies are available now through reception of the radio frequencies, together with harmonic multiplication and comparison, but they may be more conveniently available when the audio-frequency service is further developed.

Summarizing, the scientific needs for accurate time-service are constantly increasing in variety and in the degree of accuracy demanded. Adequate provision for these needs is the objective of the time services described. Both types are generally available through radio distribution, and both are of high precision.

National Bureau of Standards,
Washington, D. C.

TIME, ITS DEVELOPMENT, AND ITS FUTURE

J. F. Hellweg

A number of people are still alive who remember when every railroad had its own meridian, and by that time operated its trains. The great trunk-lines had to change here and there to adapt their time to local time. These train-times seldom if ever agreed with the local time. For instance, in the Pennsylvania Station at Pittsburgh, there were three different times, one for Philadelphia, one for some point further west, and a third, the local Pittsburgh time. The traveler was constantly in danger of missing his train owing to the doubt and confusion.

This question of time, of a universal standard time, constituted one of the most troublesome problems that had to be solved by the Nautical Almanac Office in the early days. The Observatory's old files contain the following interesting records.

In 1864, the City of Washington introduced a new telegraphic fire-alarm system. This fire-alarm system was considered a tremendous step in advance as fire-alarms could be telegraphed from one section of the city to another, expediting the handling of the fires.

The Superintendent of the Naval Observatory immediately perceived the excellent opportunity offered to extend the usefulness of the Observatory by broadcasting the time throughout the city. Prior to that, the broadcasting of time was limited to the dropping of a time-ball at noon from the flagstaff of the dome of the National Capitol.

In the fall of 1864, Lieutenant Gilliss and Professor William Harkness communicated with the Honorable Richard Wallach, Mayor of the City of Washington. Their plan was to connect the Naval Observatory by wire with the fire-alarm central office so that the fire-bells could be struck daily at 7 a.m. and 6 p.m. by telegraphic signal from the Naval Observatory.

The following summer, the middle of August, 1865, this system was inaugurated. The striking of the fire-bells in Washington therefore inaugurated the broadcasting of time. At that time the State Department was housed in an orphan asylum on 14th Street, and a special wire ran directly from the central fire-alarm office to the orphan asylum, so that the State Department could receive their noon-signal over this private wire. The Western Union Telegraph Company also had wires in the State Department building. One of their operators, appreciating the situation, immediately conceived the idea of transmitting a time-signal to their own central office each time he received the signal in the State Department from the fire-department central office. This was the real origin of the Western Union Company's connection with the United States Naval Observatory time-service, and it has continued ever since. It is rather amusing to note that in 1890 a memorial from the directors of 23 observatories requested an investigation into the system by which the Western Union Telegraph Company received its time-signal daily from the Naval Observatory.

Another step in the broadcasting of time was a circular to shipmasters, underwriters, chronometer-makers and others, issued by the Executive Office of the Western Union Telegraph Company in April 1877. The Western Union announced that an arrangement had been made with the Naval Observatory for the transmission of standard time to all cities having over 20,000 inhabitants, from Maine to Louisiana, and from the Atlantic to the Pacific. The Western Union guaranteed a direct transmission to its subscribers who would pay them a prescribed fee for this service. The directors of the 23 observatories apparently questioned why the Western Union enjoyed this sole right of the Observatory's time-signal.

But the Baltimore and Ohio Telegraph Company also received the signals and transmitted them. It is known that observatories in different parts of the country established local time-services and furnished their own determined time to railroads, cities, and individuals from which each observatory derived no inconsiderable income. Hence the strong protest when the Western Union attempted to expand its business so extensively as to affect adversely all those similarly engaged in the selling of time. The correspondence indicates considerable heat developed and the Western

Union was lambasted generally for monopolizing the business of transmitting and selling time, and for interference with the transmission of time by any local organizations.

The old records disclose a number of telegrams, letters, etc., from various communities, municipalities, etc., desiring to buy time. It is very interesting to note that Leavenworth, Kansas, wanted to buy time once a month. The Mayor of Leavenworth, considered an outstanding progressive, was willing to pay all the attending expenses in order to maintain accurate local time. His once-a-month plan was considered a stimulating step in the advancement of science and business. This monthly time-service was to be sent to the principal manufacturing jeweler of Leavenworth, and by him it was to be communicated to the city and also to the railroads. He proposed propaganda emphasizing the importance of spreading such information, the methods to be used in disseminating standard time, and the plans by which intelligent support could be developed. The Western Union Telegraph Company was advised of the City of Leavenworth's desire. It was suggested that the Western Union advertise a proposed time-service, quoting prices for monthly, bimonthly, and weekly time-service. He emphasized that there was a general desire to receive the standard time and pay for it, if necessary, but that the people throughout the country were ignorant where to apply for time and therefore the Western Union should establish and advertise a comprehensive time-service, showing scale of prices, etc.

The interesting point to us at present is that at that time accurate service once a month was considered satisfactory for all the cities who were willing to pay for it. Contrast the present demands. Until recently, we were furnishing service six times a day and that was not considered satisfactory, so we invented an automatic time-broadcaster which now shoots the signal hourly twenty times each day. The four silent hours could not be included because of radio congestion at those hours.

In 1883, Professor Simon Newcomb very strongly advocated using Washington time as the standard instead of going across the ocean to Greenwich. However, others who were pressing the measure, wanted to have a standard system for the entire world and naturally, for this international time, the meridian of Greenwich was the more suitable one.

In 1884, on invitation of our Government, an international meridian conference was held in Washington and it was agreed to establish a single prime meridian for the entire world for the measurement of longitude and for determining time. The meridian of Greenwich had already been adopted by several of the leading maritime nations, including the United States. It was therefore merely a question of having the other nations fall in line. The French insisted on the adoption of a zero-meridian passing through the Bering Strait, even after their attention was invited to the fact that the meridian of Greenwich, which passed very near Havre, cutting France from north to south, could be considered a French as well as an English meridian. It was just as much French as it was English and it could be adopted without any sacrifice of national pride. However, the French representatives were opposed to it and finally stated that they would adopt the Greenwich meridian just as soon as the English adopted the metric system. It is interesting to note in connection with this establishment of an international prime meridian at Greenwich and the French desire to place it in Bering Strait, that apparently in a previous civilization the zero-meridian was located at the eastern end of the Trans-Pacific equatorial continent at what is at present known as the Galapagos Islands and that both North and South America still show triangulation-marks based on that meridian.

After this rather interesting history of the development of the time-service, a brief synopsis of the present time-service itself follows. From the very beginning, each successive group developed its time with the greatest accuracy possible using the equipment then in existence. To read the description of the methods pursued years ago is amusing, although it is very interesting. We have travelled a long way from the fire-bell ringing in the City of Washington to the recently received information that Nanking, China, is receiving our hourly broadcast with perfect clearness and uninterrupted regularity. A Chinese scientist who visited Washington recently informed me that the signals come in clear and strong. Naturally thinking that he must be receiving one of our regular six daily signals, that subject was discussed. He interrupted by remarking, "No, we are receiving your 20-times-a-day automatic signals, and we have calculated that these signals reach us by way of the North Pole."

Accuracy of timekeeping has always been dependent upon the accuracy of the various types of clocks plus the accuracy of time-determination. Each advance in the development of clock precision was heralded with great satisfaction. For years, the nation's time has been maintained by the very best precision timepieces obtainable and has been broadcast by mean-time pendulum-controlled clocks. But what advance has been made in the accuracy of determination of time? Standard practices were jacked up, but that is all. The Naval Observatory, after experimental work over a period, has modified an instrument to meet the demands and now has a fully developed

photographic time-determination system. This photographic method eliminates the personal error and also permits repeated checking, thereby eliminating another possible source of error. The photographic method of time determination plus the automatic method of broadcasting give us the most up-to-date installation possible. It is not known whether any other nation has paralleled our latest development.

Crystal-controlled clocks have long been recognized as timekeepers of the very highest precision. Without going into the origin or the development of this system, suffice it to state that the development has centered around the design of constant-frequency oscillators and these oscillators have been developed with a high degree of accuracy. A synchronous clock driven from one of these oscillators is a correspondingly excellent timekeeper.

The constant-frequency system used at the Naval Observatory differs slightly from that employed in the usual frequency-standardization systems. It is not desirable to go into any details on this subject at the present time inasmuch as the Government has filed an application for a patent covering the invention we developed at the Naval Observatory. Two sets have been built; one is used at Mare Island and the other at the Naval Observatory. It is intended, just as soon as Congress makes funds available, to construct two more sets, one for Honolulu and one for Panama.

When the Government has patented this device, the Chinese scientist who has been visiting us for the past month wishes to purchase a complete equipment for installation at Nanking. It is devoutly hoped that he will be able to obtain the necessary funds to cover this expense as it will be a great advantage to have an American time-service, complete in all details, established in the interior of China, half-way round the world.

Without exposing any of the principles of the system, I may state that previously it required 16 minutes for the astronomer to make a chronograph-comparison between the transmitting clock with the standard clock in the vault, calculate and apply the electrical correction, and have it in all respects ready for broadcasting. Now it can be done in about five or six seconds mechanically and without chronograph-comparisons or calculations. Before, it was necessary to make this comparison previous to each broadcast, now we make this comparison twice a day although once a day would be sufficiently accurate.

After the daily comparison, the entire procedure is automatic. At five minutes before the hour it throws its own switch which makes the signal in Arlington. The master-switch has been previously thrown by the man on watch at Arlington on automatic signal from the Naval Observatory, and from that time on everything is automatic. This signal, with its identification-signals, etc., is transmitted with much greater accuracy than previously. After the signals are on the air, they are picked up by the antennae at the Observatory. They are converted into mechanical energy and operate a printing chronograph. This gives us a complete written record of every star observed, every signal going out, and every signal received over the air. These records make it possible to make extremely accurate comparisons.

U. S. Naval Observatory,
Washington, D. C.

THE ABSOLUTE VALUE OF GRAVITY AT WASHINGTON

Paul R. Heyl

The absolute determination of gravity at the National Bureau of Standards has been practically completed, only a few weeks' work yet remaining. The value found, with all the experimental corrections made that are at present possible, is 980.087, with an average departure from the mean of 0.011. The least-square probable error would be less than this, about $\pm$0.003, but on account of the considerable spread of the single results this is not a reliable criterion.

The single results ranged from 980.116 to 980.067, a spread of 0.049. In view of the fact that relative measurements of gravity can be made with a precision of about one part in a million the above result may appear rather inchoate, especially as the absolute determination at Potsdam gave a calculated probable error of $\pm$0.003. This, however, is the least-square probable error, and is the same as the similar figure for the work at Washington. A better picture of the subject is obtained by a study of the individual Potsdam results, at the stage where they are comparable with ours.

These fall into two classes, those obtained with a pendulum carrying two knife-edges and

those given by a pendulum provided with two planes. We shall quote the Potsdam values of the single results reduced to the equivalent values at the National Bureau of Standards by subtracting the difference between the value of gravity at Potsdam and at Washington which was recently determined by Lieutenant Brown. These are: (a) For two knife-edges and 108 single results, maximum 980.180, mean 980.090, minimum 980.008, spread 0.172, and average departure from mean 0.017. (b) For two planes and 84 single results, maximum 980.136, mean 980.072, minimum 979.983, spread 0.153, and average departure from mean 0.026.

It will be noticed that the spread of the Potsdam results is in one case three and a half times and in the other three times that of ours, and that the average departure from the mean is also greater in the case of the Potsdam results. The mean of the 192 observations considered of equal weight is 980.086, as compared with our value of 980.087.

The high precision often attributed to the Potsdam determination is apparent rather than real. The small calculated probable error arises from the great number of observations. The final Potsdam value (980.100 when reduced to Washington) is obtained by the mathematical treatment which was applied to the results after the stage at which we have quoted them. This treatment consisted in deriving mathematical formulas to represent certain knife-edge effects which were known to exist, though no experimental methods were available for direct determination of their magnitude. The separate results were grouped into 9 classes, and least-square normal-equations were obtained for the knife-edge effects in each class. The following values of g (at Washington) resulted:

980.100	980.106	980.099
095	105	099
095	101	099

The first six values of these were rejected for various reasons, and the last three retained. An additional correction of 0.001 was made to allow for certain variations in length-measurements, and the final value of 980.100 obtained.

Our value of 980.087 has not been subjected to this mathematical treatment, as we consider it not sufficiently well founded. Our value is probably a little low, by an amount at present experimentally indeterminable, due to knife-edge errors, principally variable friction. This point is receiving further study at present.

National Bureau of Standards,
Washington, D. C.

MAPPING THE COUNTRY

William Bowie

I have appeared before the Section of Geodesy of the American Geophysical Union a number of times as a speaker on geodetic subjects. Today I shall cover a wider field, the field of mapping. Mapping is a fact-finding process. Without the facts furnished by maps, geophysicists, geodesists, geologists, and others have difficulty in planning and executing their operations.

Need for maps--This country is very poorly mapped. While 45 per cent of its area is covered by topographic maps, only about one-half of those maps are adequate for modern use. This means that about 75 per cent of our three million square miles have no topographic maps or have maps that are not serviceable. This is a situation that needs correction.

The activities of our 125 million people are very great. They follow all lines involving production, transportation, commerce, and science. These activities have been going along without much direction. Each individual or group of individuals has done about as it wanted or was permitted to do. This method is probably undergoing a change. We are now hearing much of planning. This includes planning for the country as a whole and planning for subdivisions of its area. There is planning for transportation, for utilization of land, water, and forests, for prevention of soil-erosion, and for many other things, and the planners are becoming aware of the difficulties involved in working without facts. They believe that if the country were topographically mapped, the maps would show just the information that they need.

Comprehensive plans for mapping the country--The Federal Board of Surveys and Maps in October, 1934, prepared a plan for the completion of the topographic mapping of the country within ten years. This plan was submitted to the National Resources Board. The latter Board ap-

proved the plan and has printed it in a report to the President.

The national plan calls for the expenditure of $117,000,000 within a ten-year period. About $20,000,000 of that amount would be devoted to geodetic surveys which, as is well known, furnish precise data regarding position, elevation, distance, and direction of monumented points over the area of the country. These control-survey stations are to be spaced at intervals of approximately six or seven miles. That spacing is needed by map-makers in compiling maps from photographs taken from the air and by engineers working on the ground in locating contours on the maps. The results of the geodetic surveys will not only furnish the necessary framework for topographic maps but they will also be of much value in many classes of engineering, for the location and perpetuation of the boundary-lines of private and public land, and for scientific uses.

Geodetic surveys--Geodetic data are used in determining the figure of the Earth. They furnish about the only means for making a test of the isostatic condition of the crust of the Earth. They are also used (and will continue to be) to determine the extent to which earth-movements occur during earthquakes. After an earthquake it will be possible, by repeating observations on bench-marks and at triangulation-stations, to determine the extent of the disturbed area in the vicinity of the epicenter of the earthquake. This is a geophysical and geological problem involving the question of whether the cause of an earthquake is local or regional. If local, then probably the distorted area in the vicinity of the epicenter will be found to be limited in extent.

The Coast and Geodetic Survey has for many years been extending lines of levels and arcs of triangulation over the country. In recent years, readjustments of the triangulation- and leveling-nets have been made, and so far as practical uses are concerned, it is likely that no readjustment of the nets will be needed in the future. New arcs and lines can now be fitted into the nets without upsetting the adjusted work except in a few cases where the closing error of a loop of leveling-lines may be of such size as to throw undue correction into the new line. In such a case some of the adjusted lines involved in the loop are changed slightly in order to make a smaller rate of correction as the new line is fitted to the net.

At many of the triangulation-stations observations for the astronomical latitude and longitude have been made. The comparison of the astronomical and geodetic data shows variable differences that are due to the irregular surface of the Earth and also to masses of rock of abnormal densities near the stations. These differences are called deflections of the vertical and give some indication of buried geological structures.

Topographic maps--In making any geophysical measurements and observations a knowledge of the terrain is most desirable. Therefore, the completion of the topographic mapping will be of great benefit to the geophysicists. This is especially true in the fields of hydrology, meteorology, terrestrial magnetism, and geodesy.

The Earth's surface has not always been as it is now. Great changes have occurred. What are now mountain areas were once covered by tidal waters and the areas where mountains formerly existed are now leveled off in many cases or may even be below sea-level. One of the principal problems of geophysicists and geologists is to discover if possible, from observations and accumulated data, just what causes these changes. The final answer to this question may never be learned, but in any event a knowledge of the configuration of the Earth's surface as furnished by topographic maps will be of great assistance in the attempt to solve the problem.

The human race has a limited area on which to live and work, and natural resources are practically limited. There are now about two billion people in the world and the number is increasing steadily. With increase in population but no increase in resources the latter become relatively scarcer and more valuable. It seems to me that surveys should be made of our natural resources with geophysical and geological surveys playing an important part. However, such surveys can not be made with any degree of effectiveness unless topographic maps are available.

The present plans call for maps to be made of such scales as are needed to meet the requirements of map-users. In some areas, highly developed industrially and otherwise, the scales will be large. In mountain areas or in the plains regions where industry is not carried on extensively, maps of smaller scale will be adequate. Every effort will be made, no doubt, to fit the scale of the map and the details shown on it to the needs that exist in any particular part of our area. In every part of the country, however, the data shown on the maps will be most valuable in carrying on the work of our people, and any expenditure made for these maps should be considered as an investment. I know of no investment that will pay such large dividends to our country.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE GEORGIAN BAY SECTION OF ONTARIO TRIANGULATION

Noel J. Ogilvie

The closure of a triangulation-loop seldom fails to stimulate interest among those engaged on geodetic work. Checks on the accuracy of the field-work, through the use of side-and-angle equations, the inclusion of Laplace joints, and the measurement of base-lines, do much to indicate the general accuracy of the work; but it must be admitted that the crucial test of the observer's care and skill is ultimately made by means of the loop-closures of the triangulation-arcs.

The completion, in 1934, of the Georgian Bay section of Ontario triangulation resulted in the closure of a loop having an axial length of about 800 miles. The loop consists of an arc of triangulation extending eastward from the north end of Georgian Bay, through the Sudbury mining district and along the Ottawa River as far as Ottawa. From Ottawa, it is composed of part of the Southeastern and Southwestern Ontario nets, extending southerly to the St. Lawrence, thence westerly along Lake Ontario and Lake Erie, thence northerly as far as Georgian Bay. The area covered by Georgian Bay and some of the adjacent territory constitutes the section of triangulation under discussion.

The field-work on this section was carried out during the field seasons of 1933 and 1934. The original scheme of reconnaissance, laid down to bridge the gap, involved five geometrical figures having triangle sides up to 80 miles in length. By straddling the Bay with large-sized figures it was considered that the cost of the project would be less than that of any alternative scheme where shorter lines were used.

In carrying out the reconnaissance, it was realized that, due to the low elevation of the topography, it would be impossible to choose stations having elevations sufficiently great to permit of the intervisibility of all stations under normal conditions of vertical refraction.

Previous experience of engineers of the Geodetic Survey of Canada, Department of the Interior, on similar work in the Gulf of St. Lawrence and the Maritime Provinces, indicated that values of abnormal vertical refraction, as much as two or three times the normal amount, might be expected to obtain sufficiently often to allow the observing parties to secure observations over the lines, without excessive delay.

To expedite the work, provision was made for the simultaneous instrumental occupation of seven or eight triangulation-stations. Unfortunately, June and July, two of the most favorable months for the taking of observations, had already passed before it was possible for the observational work to be commenced. This delay greatly lessened the possibility of successfully completing the work during that season.

Where abnormal conditions of vertical refraction must be relied upon to permit of the intervisibility of stations, the spring months are considered, by some geodetic engineers, to be much more favorable than the latter part of the season. The reasons advanced for this belief are summarized below. [See also J. L. Rannie (Supervisor of Triangulation, Geodetic Survey of Canada), Mirages and other abnormalities of vertical refraction, Canadian Surveyor, v. 5, 12, 1934.]

The vertical curvature or refraction of the sight-line, to any distant point, is caused primarily by the passage of the line through successive layers of air of different densities at increased elevations above sea-level. Usually, a condition of decreased air-density at increased elevation has been found to obtain. The atmosphere, therefore, may be regarded as a large refracting lens. Within this huge complex lens, smaller component lenses having refracting characteristics totally different from that of the main atmosphere may exist for short periods of time, due to peculiar local conditions.

The path of a line of sight may be studied by means of certain formulae involving temperature, considered as a variable. According to Müller-Pouillet (Physik der Erde, v. 1, part 1, p. 209), at a temperature of 0° C and a pressure of 30 inches, if the temperature decreases at a rate of more than 3.4° C per 100 meters of height, the increase in air-density due to temperature-decrease more than equalizes the natural density-decrease due to greater height and results in an actual increase in air-density at an increased elevation. When this condition occurs, the light-path is concave on the upper side--a condition productive of mirages.

If the air becomes cooler at the rate of 3.4° C per 100 meters rise in elevation, the increase in density of the air, due to this cause, exactly equals the natural decrease in air-

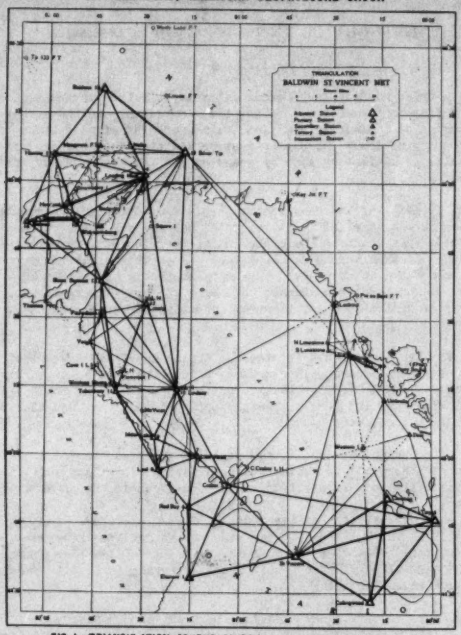

FIG. 1—TRIANGULATION-SCHEME COVERING THE GEORGIAN-BAY AREA

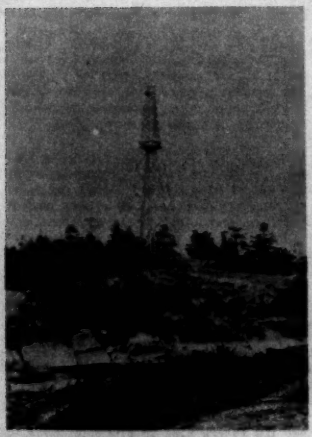

FIG. 2—100-FOOT TRIANGULATION-TOWER AT "LOOKOUT"

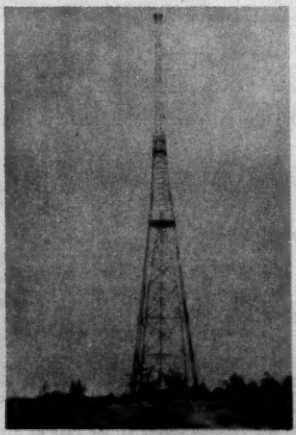

FIG. 3—SAME AS FIG. 2 WITH 80 FEET OF EXTENSION-LADDER SUPERIMPOSED

density, due to the increase in height. In this case, the resultant of the two influences is zero and the air-density is the same at different elevations. For this atmospheric condition, the path of a light-ray is a straight line.

On the other hand, if the temperature increases with increased height it will, of course, result in a lessening of the air-density. This decrease taken in conjunction with the natural decrease of air-density, due to increased height, results in an extreme lessening of the air-density per unit of height and it will result in an abnormal vertical refraction of the line of sight, concave on the lower side. This condition, causing distant objects to appear higher in the sky than they ordinarily appear, is believed to occur more often in the early part of the night.

After sunset, the layer of air next to the surface of the sea or a cold lake may be expected to cool rapidly, at the same time becoming more dense. The rate of pressure decrease with respect to height would then become greater, thus producing a greater arching of the line of sight from a distant point near the Earth's surface. Distant objects would then appear to be at a higher elevation than usual and some objects, that were previously obscured by the curvature of the Earth, would become visible due to the excessive refraction of the line of sight. In general, it may be inferred that when cold air is drawn in at the surface of the Earth, or warm air is supplied at some elevation above the surface, the conditions are favorable for the occurrence of abnormal refraction.

In the early spring, when ice still remains on the surfaces of the lakes or while the lake-water still remains cold and the northward-moving Sun warms the upper atmosphere, it is argued that we may expect an occurrence of the atmospheric conditions just mentioned. In the fall, conditions productive of abnormal refraction, would not be expected to occur with much frequency.

While the above theory appears to merit consideration, yet it cannot be entirely substantiated by the experience of field-officers of the Geodetic Survey of Canada. J. E. R. Ross, Chief of our Division of Office Adjustments, formerly in charge of the projection of an extensive triangulation-network in the Maritime Provinces, states that conditions of abnormal refraction were found to occur in that locality equally often in one month as another.

The progress of the observation-parties on the Georgian Bay section of Ontario triangulation was retarded in 1933 to a certain extent by the infrequent occurrence of the conditions producing abnormal refraction. This may be attributed perhaps to the advanced state of the season when the work was commenced.

On the approach of fall, it was considered desirable to withdraw the parties from the field and to complete the work the following spring, when more favorable atmospheric conditions might be expected.

In the spring of 1934, the triangulation was resumed. Instead of relying entirely on the securing of observations over all the difficult lines, which had given trouble the preceding fall, a few modifications were made in the scheme. By including some additional stations, involving shorter lines, an alternative plan was worked out. This scheme proved to be feasible and led to the quick completion of the gap in this important loop of Canadian triangulation.

Several phases of the field-work merit special mention. The reconnaissance was carried out by a reconnaissance engineer assisted by another experienced engineer. Equipped with a portable extension-ladder, which was transported easily on a one-ton truck, the party was able to move quickly from place to place and, although they were greatly handicapped by having the tower-building party figuratively speaking on their heels, they were able to proceed with the selection of observation-stations with little or no delay to the tower builders.

During the course of the season's work, the reconnaissance party was delayed by a line, blocked by a wooded ridge about three miles distant from one of the terminal stations. The removal of several trees on the ridge was decided upon. As the distance between stations was only 12 miles, it was thought that the bearing of the connecting line might be determined by recourse to the use of sky-rockets. Accordingly, with watches synchronized, an engineer at one of the terminal stations was to send up a series of five rockets at prearranged intervals of time, while the reconnaissance engineer watched from the other terminal station. It was hoped that, with the aid of a small transit, the desired bearing might be secured just about dusk.

Unfortunately, only one good rocket could be secured in the entire neighborhood. The ascent of this, the first rocket, was easily seen with the naked eye by the engineer on watch and an approximate bearing of the line determined. As the other rockets failed to rise, the experiment

could not be carried to a successful conclusion. Sufficient information was secured, however, to prove the idea feasible for lines of reasonable length.

The tower-building party, composed of the chief and six men, was successful in the rather hurried construction of the requisite towers. The towers, ranging from 30 to 60 feet in height, were built almost entirely from sawed lumber, purchased from local mills. Eleven structures were completed during the 1934 season in 44 working days, including the time spent in going from and returning to Ottawa.

Particular attention is invited to the erection of a 60-foot length of portable extension-ladder, on top of the 100-foot tower already built at "Lookout." This extension was to serve only as a lamp-stand over the station, which had been previously occupied.

The portable extension-ladder was hauled, section by section, to the top of the 100-foot structure. From an improvised platform constructed 7 or 8 feet below the top, the extension-ladder was erected, section by section, in the manner customarily adopted for erection on the ground. Four sets of long guy-wires were attached at intervals along the length of the 60-foot extension. On the top, 150 feet above the ground, a small platform was attached to serve as a lamp-stand for the electric signal-lamps. When the required observations had been completed to this station, the extension-ladder was removed in the usual manner.

The measurement of the horizontal angles in 1934 was carried out principally by one party. A few of the outlying stations, on islands and points difficult of access, were occupied simultaneously by additional observers. Fourteen stations were observed in all, eight by the main observing party and six by the other observers.

The work of the main observation-party was considerably increased by the failure of the automatic time-switches to function at all times. As no light-keeper had been attached to the observing party, to act in such emergencies, the personnel of the observing party were sometimes obliged to carry out their regular work of observation at night and to spend much of the following day in making long trips to investigate the cause of the non-appearance of signal-lights at neighboring stations. Some of the trouble experienced with the signal-lamps and batteries no doubt resulted from interference.

The accuracy of the triangulation, as revealed by the closure of this loop, shows that the work was of an exceptionally high standard for primary triangulation. The actual closure of the loop, after the adjustment of the component nets, was about 12 feet in the 800 miles of axial length. Much of the axial length of the loop was, however, composed of parts of the Southeastern and Southwestern Ontario nets, which are without doubt among the most accurate sections of triangulation ever carried out by the Geodetic Survey of Canada.

In connection with the adopted Georgian Bay section of this loop, the average triangular closure of 68 triangles is 0".80. The maximum triangular closure is 2".31. The side-equations also indicate that the measurement of horizontal angles was not below the customary standard of accuracy maintained in the projection of primary triangulation.

During the past few years, the necessity of tying triangulation-stations to local township lot-corners has been repeatedly emphasized. The importance of such survey connections is becoming more fully recognized by both Provincial and Federal survey bureaus. On the Georgian Bay work special efforts were made by the observation-party to secure adequate survey-connections to township- and lot-corners.

Where triangulation-stations are established in settled communities, the following method of enhancing the usefulness of geodetic control has recently been suggested by one of our engineers (W. C. Murdie, Geodetic Engineer). The suggestion involves the establishment of the usual standard concrete monument at the triangulation-station, together with two additional reference monuments along the edge of some nearby road allowance--say from one-half mile to two miles distant. The distance between the reference-monuments, on the road allowance, might be one-half mile or more, as local conditions would warrant.

The idea behind this system of monumenting and referencing of geodetic points is to render the loss of the original control-point, through the destructive agencies of time and vandalism, less probable, and at the same time to make available at each geodetic station two reference-points at a considerable distance apart. The reference-monuments would then serve as a measured base-line for local survey-work, carried on by Provincial surveyors or engineers. In addition, any two of the monuments would provide a well-determined geodetic azimuth for similar purposes.

A few years after the completion of the geodetic observations at a station, the tripod and tower usually collapse. The inability to see out to neighboring geodetic stations from the ground precludes the possibility of securing a local azimuth-mark, where only a single monument has been constructed.

During the stay at each station, the geodetic observation-party engaged on the measurement of the horizontal angles would have as part of its regular duties the task of carefully measuring the distance between the roadside reference-monuments. It would also determine the geodetic azimuth of the line joining the roadside monuments as well as the azimuth from each of these points to the geodetic observation-station.

By this method, the recovery in after years of either of the two widely-separated road-monuments would be sufficient to permit of the relocation of the original geodetic station in case of its destruction. Of equal importance would be the stepping down of the main triangulation-scheme to a local three-point scheme, with two points placed close to a road where they would be easily accessible to the general public. The local base-line and azimuths made available at each station by this system would add greatly to the general utility of geodetic survey-control. Too much emphasis cannot be given to the fact that much of the usefulness of a geodetic control-point is lost by not stepping down some form of local control. A single geodetic station, situated on the summit of a mountain or hill, does not fully serve the purpose for which it was intended. Local engineers have neither the time nor the equipment necessary to carry surveys down from a network of widely-spaced primary or secondary triangulation-stations, established for the main part on the summit of mountains and hills almost inaccessible for local surveying and engineering purposes. In rendering greater service in a more practical manner, geodetic surveys will become more appreciated by the public in general.

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SURVEYS IN AGUASCALIENTES BY PHOTOGRAMMETRIC METHODS

Manuel Medina

As soon as the program was planned for the geographical survey of the State of Aguascalientes it became necessary to modernize the proposed map by the acquisition of topographic data in order that it might include information needed for all purposes involved in the utilization of the area. Surveys both on the ground and from the air were considered in formulating the program for the final field-operations.

The essential difference between these two photogrammetric processes is that the first is preferable for contouring and the second for obtaining a mosaic showing the features of the area in horizontal projection. When both operations are controlled by basic surveys, the land photogrammetry gives a precision very superior to that of the aerial survey, because the distance from the photographic plate to the object and the angle of the plane of the plate are known. For this reason, the terrestrial method was selected for the detailed map of Aguascalientes. Another reason for this choice was the fact that the major part, if not the entire area, had been covered by the ordinary methods of surveying (traverses, intersections, resections, etc.) by means of which a map of the territory had been made and it was only necessary to put in the contour-lines.

In this paper is given in brief form a description of the photogrammetric operations carried out in the State of Aguascalientes, which constitute the first application that has been made in this country of terrestrial photogrammetry for putting contour-lines on geographic maps.

The photogrammetric party was ordered to operate in the State of Aguascalientes with special instructions to obtain plates at such places as to give a configuration of the country to a scale of 1:100,000, and with a contour-interval of 50 meters. The party was composed of a chief engineer, who was also to operate the camera, an assistant engineer, who was to locate suitable points of control and who was in general charge of the transit-work, an aid, who was in general charge of the camp and who did clerical work, and a variable number of "peons" locally engaged.

The party carried the following equipment: A complete Zeiss outfit for terrestrial photogrammetry, Model C 3/b; a one-minute theodolite (Bausch and Lomb); two "Neri" and two "Prieto" stadia-instruments (the "Neri" being used for the bases and the "Prieto" for the traverses that were run to locate control-points); steel tapes; targets; compasses; etc.

The party had for transportation a two-ton Ford truck, two horses, and six pack-mules. The equipment included utensils for camping, a canvas tent, and miscellaneous equipment needed for life in the field and for making clearings.

Reconnaissance--The reconnaissance consisted in locating stereophotogrammetric bases and stations for the camera in such a manner that the photographic sectors would embrace all the territory to be surveyed without any gaps, and of determining the manner of tying in to the triangulation the position of the camera, whether by means of subsidiary triangles, short traverses, intersections, or resections.

Position of camera--In the two seasons of work completed by the photogrammetric party, 61 bases were chosen and measured, thus locating 122 positions of the camera. Since the area of the State is 5500 square kilometers, this corresponds to one stereophotogrammetric base for each 90 square kilometers for use in mapping on a scale of 1:100,000 with contour-interval of 50 meters.

Measuring photogrammetric bases--A suitable place for a base having been chosen, its direction was fixed so that the photographs would cover the needed zone. These directions were marked provisionally and by means of a prismatic instrument the lateral boundaries were observed. Knowing these, the boundaries in distance were calculated by making use of the formula

$$B = Aa/f \quad \text{or} \quad A = Bf/a$$

in which A is the distance to be evaluated, B is the length of the base, a is the parallax, and f is the focal distance of the camera.

In this formula, B is determined by direct measure, f is known for each camera, and a is a variable coefficient of parallax, which, if kept between 5 and 40, determines the distance which can be obtained afterward in the stereoautograph. With values of parallax less than 5 it is not possible to obtain stereoscopic vision nor is it with values greater than 40. The limiting values were taken as 15 and 30 therefore in obtaining the minimum and maximum range for the zone embraced by the station.

In the stereophotogrammetric work for geographic application, one should not lose sight of the fact that the most minute detail will not be as useful as the general configuration of the topography, because in each case one must take into account the contour-interval as well as the scale of the map. It is well, therefore, not to choose bases too small as with these details are obtained that are not appreciable on the geographic map.

A base having been chosen and its ends precisely marked, the following three operations must be carried out in addition to the camera work: The base must be measured, its azimuth must be determined, and the position of one end must be determined. In the greater part of the Aguascalientes work the bases were measured simply with one stadia-sight.

With a good position for the extreme A-end of the base (this name being given the left end facing the area to be photographed) and with the position of the camera carefully fixed, there is no necessity of having an accurate base-measure, because the stereoautograph will expose the error of measure and provide the means of correcting it. That is to say, if all the other data are true, it may be considered for all practical purposes that the length of the base can be varied within small limits. Since only the measurement of the base takes much time, a quick method for this measurement should be adopted. Nevertheless, one has very serious difficulties in geographic work, since the mean distance to be measured is 700 or 800 meters and on many bases in Aguascalientes measurements up to more than 1600 meters were made by one stadia-sight. Table 1 gives the length of the base for each of 57 of the stations utilized as I believe this work can ultimately be standardized and, therefore, that conclusions can be drawn from these first statistics.

The mean length of base for the 57 stations is 1032 meters, from which is seen that in many cases the measurement with stadia-transit passes the limits of tolerance. The stations that appear with lengths of more than 2 km do not mean that they were measured thus. Bases for 38 and 40 (whose lengths are not given here with precision) were calculated since the ends are primary triangulation-points (38A which is the same as 40B is San Juan hill and 38B-40A is the station "Altamira") and the precise distance was obtained from coordinates of the ends.

In some other cases angles were measured to close a triangle one of whose sides was a photogrammetric base to be computed--on Ardilla hill--and finally for the base at "Bancos de Mexico" the two ends were located separately by resection.

FIG. 1—DIAGRAM OF GEODETIC AND TOPOGRAPHIC SURVEY

LEGEND

a—b ANGLE AND SIDE OF GEODETIC TRIANGULATION

a'—b' ANGLE AND SIDE OF TOPOGRAPHIC TRIANGULATION

LOCATION BY MEANS OF INTERSECTIONS

MOJ. LA FRONTERA
EXTR. N. BASE
C. ARDILLAT
CABRITO
C. ALTAMIRA
RINCON DE ROMOS
EXTR. S. BASE
ASIENTOS
PABELLON CITO
CHIQUIHUITE
C. FINAL
C. CHICHIMECO
C. GORDO
S. JOSE DE GUADALUPE
HDA. LA LABOR
PUERTECITO
NEGROS
JESUS MARIA
C. PAPANTON
C. ALTO
C. PALO ALTO
S. IGNACIO
TERRERO
S. ANTONIO
C. PICACHO
AGUASCALIENTES
S. JOSE DE BUENAVISTA
CALVILLO
VIVISADERO
MOJ. FRONTERA
C. ESPERANZA
C. DE LA LUZ
C. MUJERES
HDA. DE LA PUNTA (JAL.)
C. DELGADILLO
C. LA CAMPANA
C. ELT
HDA. CHINEGUILLAS
MOJ. LA SALAMANCA
HDA. DE PEÑUELAS
C. LA CULEBRA (TAC.)
C. OF. LOS GALLOS

FIG. 2—DIAGRAM OF STEREOPHOTOGRAMMETRIC SURVEYS

Table 1--Lengths of base-lines at stations

Station number	Length of base	Station number	Length of base	Station number	Length of base
	meters		meters		meters
1	1110	22	3194	41	368
2	950	23	1120	42	1141
3	825	24	654	43	1050
4	1410	25	920	44	1340
5	970	26	463	45	840
6	660	27	2060	46	926
7	450	28	988	47	400
9	1170	29	471	48	643
10	472	30	321	49	725
11	904	31	584	50	1920
13	1570	32	387	51	910
14	1035	33	280	52	582
15	1316	34	534	53	1220
16	847	35	408	54	841
17	1620	36	393	55	2300
18	285	37	1640	56	891
19	523	38	3000	57	2040
20	1366	39	368	58	1050
21	757	40	3000	59	840

In practice the method used for measuring the bases which exceeded 400 meters in length was to utilize one of the stadia-metric threads with the horizontal wire in the diaphragm of the instrument, multiplying the stadia-reading by 200, and when the distance exceeded 800 meters, one or even two targets were fastened to the stadia-rod with the graduations made to correspond exactly, thus giving a stadia-rod up to 7 meters with a corresponding distance up to 1400 meters.

In practice we found afterward that even for distances of 1200 or 1300 meters, the error was less than 10 meters. One must not lose sight of two things: First, since the photogrammetric surveys are made for geographic detail and to delineate the topography of the area, each important feature ought to be determined beforehand, with its three coordinates; and second, one must use much care in the location of the camera-stations in order that sufficient control-points will be photographed on each plate.

Position of one end and azimuth of the base--There is an advantage in many cases in utilizing the stations of the geodetic or topographic triangulation to tie in the photogrammetric base directly. In such cases the problem of location was readily solved and the azimuth was obtained by measuring the angle between one side of the triangulation and the base.

In other cases location by resections was utilized. This procedure is almost always possible as the photogrammetric station has sufficient height to give visibility over a wide area.

In these angular measurements we emplyed the Zeiss theodolite of the equipment which has already been mentioned (No. 16384). It reads to 2" in both circles, has an optical micrometer, and a horizontal circle which is graduated clockwise.

Although the instrument has great accuracy, it was used in only one setting of the circle with one direct and one reverse reading and no effort was made to make precise pointings as a direction to the nearest minute was sufficient. The same approximation can be used for the azimuth.

Figures 1 and 2 show in a general way how the work was done.

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INTERNATIONAL STANDARDIZATION OF BASE-LINE TAPES AND WIRES

Lewis V. Judson

(Publication approved by the Director of the National Bureau of Standards of the United States Department of Commerce)

The International Bureau of Weights and Measures has sent a group of invar base-line wires for standardization to several of the national laboratories. Twenty-four-meter invar wires are used rather generally in Europe for geodetic base-line work instead of the 50-meter base-line tapes used by the United States Coast and Geodetic Survey. These wires are described in "La mesure rapide des bases geodésiques" by J. R. Benoit and C. E. Guillaume.

The standardization of these wires at the International Bureau is carried out in a basement-room in the main laboratory building. The new equipment, installed a few years ago, is described by Dr. Guillaume in an article entitled "La nouvelle base edifiée au Bureau International," published in the "Proces-verbaux des seances" of the International Committee for the session of 1925. The working standard for the measurements is an H-shaped four-meter invar bar.

The equipment for standardizing tapes and wires is different in nearly every country. Some of these comparators were described in a paper "Precision machines and instruments for the measurement of length," presented by Dr. George K. Burgess at the World Engineering Congress in Tokyo in 1929 and published as paper No. 335 in volume 5 of the Proceedings.

Because of the considerable differences between the several installations it had been felt for many years that there should be an international standardization of a group of wires and this program is now being carried out. The National Bureau of Standards requested that it be included in the program, and a similar request was made from Ottawa.

The wires have been standardized in Washington twice, first in 1933 and the second time in 1934-35. Twenty-four-meter tapes belonging to the National Bureau of Standards and to the Physical Testing Laboratory of the National Research Council at Ottawa were included in the more recent series of measurements.

The outcome of these measurements may be stated as follows: (a) The National Bureau of Standards, the Physical Testing Laboratory of the National Research Council at Ottawa, and the Geodetic Survey of Canada appear to be in agreement with the International Bureau of Weights and Measures on lengths of 24-meter bases to at least one part in a million; (b) The instability of the tapes and wires used in these measurements, and the uncertainties in the coefficient of expansion make it impossible to determine the actual agreement to a higher degree of accuracy than that stated.

I wish to acknowledge gratefully the cooperation of B. L. Page and R. F. Ackermann in the measurements at this Bureau.

National Bureau of Standards,
Washington, D. C.

PROGRESS OF THE GEODETIC WORK OF THE COAST AND GEODETIC SURVEY DURING APRIL 1934 TO MARCH 1935

C. L. Garner

Geodetic work in the United States during the last twelve months has been the greatest in history. Between April 1, 1934, and March 31, 1935, there has been completed a total of 19,117 miles of first- and second-order triangulation and approximately 116,000 miles of first- and second-order leveling, distributed in practically all of the states and made possible through the use of regular appropriations and augmented by emergency funds appropriated for the relief of unemployment under the provisions of the National Industrial Recovery Act of 1933-35. This class of work appeals to the authorities seeking ways and means of distributing relief through channels by which the Government will obtain a service which will ultimately contribute greatly to the utilization and conservation of the natural resources of this country. This appeal is further strengthened by the fact that a very large proportion of funds, about 70 per cent, is spent directly for personnel services.

Scope of geodetic work--Geodetic work consists of the extension of first- and second-order

triangulation and traverse, lines of first- and second-order leveling, astronomical observations at certain of the triangulation-stations, base-measurements, gravity-observations, observations for the variation of latitude at Ukiah (California) and Gaithersburg (Maryland), and the work in the Washington Office as required for the computation and publication of the results.

The horizontal control-work or triangulation-system provides permanently marked monuments distributed over the country and adjusted into a strong Federal net for the use of all engineering and surveying operations. This gives the coordination which is essential to all large-plan works and which avoids duplication, overlapping, and waste in industry. The same principle applies to the vertical control, consisting of first- and second-order leveling by means of which bench-marks are established and their elevations above mean sea-level are accurately determined. These accurate elevations are distributed over the United States on a single coordinated datum for the purpose of obtaining uniformity and eliminating the wasteful processes which obtained when many standards of elevation were in use.

It was only a few years ago when one of the cities of this country had as many as ten different datum-planes of elevation for the extension of its engineering works throughout its corporate limits. It is apparent that the extension of engineering works and building projects of various kinds, so essential to city life, upon so many different standards would eventually lead to a tremendous amount of wasted effort, confusion, and unnecessary expense. One purpose of the horizontal and vertical control-nets of the United States, therefore, is to furnish standard, fixed, and rigid horizontal and vertical datums for the use of engineers and others interested in any area where such data can be put to a worth-while service.

The total control-work completed in this country to April 1, 1935, is: Triangulation--first-order 57,831, second-order 6,359, total 64,190 (total needed to complete 25-mile spacing 54,600); leveling--first-order 102,485, second-order 121,918, total 224,403.

At the present rate of progress the leveling will be completed for the 25-mile spacing by June 30, 1935. The cost of the work executed during the past twelve months was approximately $2,650,000 and provided employment for over 1200 men.

Other geodetic work in the United States, as previously mentioned, includes determination of the relative intensity of gravity at stations in the United States and outlying islands. It also includes observations for the variation of latitude at Ukiah (California) and Gaithersburg (Maryland). The latter are two of the five stations of the international net which are used by the Joint Committee on Variation of Latitudes of the International Astronomical Union and the International Union of Geodesy and Geophysics in investigations regarding variations in position of the pole of the Earth. The observatory at Ukiah has been in continuous operation for a period of 35 years, while the work at Gaithersburg has been in operation from 1899 to the present, except for an inactive period from 1915-32, inclusive. Geodetic work also includes astronomical observations which consist of the determinations of latitudes, longitudes, and azimuths at certain of our triangulation-stations. These and the base-measurements are essentially a part of the control-work but they also furnish valuable scientific data used in studying the figure of the Earth and in carrying on certain geophysical investigations. The base-measurements are made at intervals along the arcs of triangulation as a means of controlling the lengths within certain limits. Laplace azimuth-observations are made at stations at intervals of approximately eight figures along the schemes of triangulation in order that the azimuths or directions of the lines may be held to required limits of accuracy.

Cooperation with other organizations--The Coast and Geodetic Survey is by law charged with the responsibility for these surveys and performs practically all of such work in this country. The Bureau is ever ready to cooperate with other agencies in the extension of this class of work wherever such data are most urgently needed, and to obtain by exchange from agencies who have executed acceptable work independently, data which may be adjusted into the Federal scheme and made a part of it. Such cooperation has been carried on with the Army Engineers, the Mississippi River Commission, the Bureau of Reclamation, and United States Forest Service, and others.

A party of the Coast and Geodetic Survey is now engaged in first-order triangulation and astronomical observations in cooperation with the Commision Tecnica de Demarcacion of Guatemala-Honduras. This work is required to control detailed surveys which are being made as a means of settling the boundary-dispute between those two countries.

A field-party is now engaged in the extension of lines of levels in seismic regions in Southern California in cooperation with the Advisory Committee in Seismology of the Carnegie Institution of Washington. The monuments for which the elevations are being determined will also be included in a scheme of triangulation to be extended this winter. This will locate monuments

both horizontally and vertically and by repeating the observations from time to time as conditions justify there will be afforded a means of studying any movements either horizontal or vertical which may take place within the area. Lines of levels for similar purposes were extended in the vicinity of Long Beach (California) and in the vicinity of Kosmo (Utah) earlier in the year. A considerable amount of leveling has also been done in the general region of San Jose, California, for the purpose of studying the various factors connected with the subsidence of the Earth in that region.

Two of the parties of the Bureau are extending triangulation and lines of leveling and are making traverse-measurements at Boulder Dam and vicinity in cooperation with the Bureau of Reclamation and the Soil Erosion Service as required for special studies involving the water-load to be impounded in the Reservoir. The Bureau of Reclamation is interested in the possible deformation of the dam-structure and of the surrounding terrain which may result from the water-load. The Soil Erosion Service is to study the question of silting and is making a survey which will be repeated from time to time to reveal the rate and amount of silting in the basin. The Coast and Geodetic Survey is cooperating to the extent of furnishing horizontal and vertical control for their work.

The horizontal and vertical control-work to the 25-mile spacing in the Tennessee Basin was completed early last fall in accordance with the plan which was reported at last year's meeting. This work was computed and adjusted in the Washington Office, and officials of the Tennessee Valley Authority were furnished full data covering this work promptly upon its completion. From reports which have reached us it is certain that the data furnished the Tennessee Valley Authority have been of inestimable value in connection with their mapping activities.

Local control-surveys--Last year's report included a statement concerning the local state-control which had been extended in the various states under the auspices of the Coast and Geodetic Survey in cooperation with the Civil Works Administration. The local state-control surveys in fifteen states have been in continuous operation since their inception about sixteen months ago. The total amount of local control-work accomplished in all of the states since the beginning of this class of work more than a year ago is 31,500 miles of second-order traverse and 38,500 miles of second-order levels. It is of interest to report that in South Carolina there have been completed upwards of 4500 miles of lines of traverse and leveling of second-order accuracy or better; and in Georgia approximately 3600 miles of lines of traverse and leveling of second-order accuracy. However, before such surveys can be of their greatest value to the local communities it is essential that they be connected and coordinated with the fixed control-net. For this purpose it was necessary to complete the triangulation and leveling to the 25-mile interval in those two states as a means of bringing into coordination the local surveys and placing the entire work on the Federal horizontal and vertical control-datums. The leveling has already been completed to the 25-mile spacing and it is anticipated that the triangulation will be completed by April 30.

Similar work in other states is in progress. Reconnaissance is now being extended in New Jersey, Connecticut, and Massachusetts, and will be followed in the immediate future by triangulation, as a means of completing the 25-mile spacing of the horizontal control-surveys in those states in order to meet the requests received from the United States Geological Survey and other organizations for mapping purposes.

Gravity-determinations--One of our field-parties has been in continuous operation throughout the year making gravity-observations in Connecticut, Wyoming, Montana, Florida, and Cuba. The observations in Connecticut were made at the request of Professor Chester R. Longwell of Yale University; those in Wyoming and Montana were made on the recommendation of a committee engaged in geological studies headed by Professor W. T. Thom, Jr., of Princeton University; and the work in Cuba was in cooperation with the Atlantic Refining Company of Cuba and was initiated by the Committee on Geophysical and Geological Study of Oceanic Basins, of which Professor Richard M. Field of Princeton University is Chairman. The gravity-party working in Cuba has completed 84 stations during the past winter.

Nearly all of our gravity-observations within the last two years have been made with the Brown apparatus, which is much faster than the older type. As many as 25 stations have been occupied in one month with this apparatus. The instrument has proved so successful that two more sets of the Brown gravity-apparatus are now being manufactured.

The Bureau has also arranged for the purchase of a Holweck-Lejay gravity-apparatus. Delivery of this instrument is anticipated some time within the next three or four months. This instrument is very light and is reported to be capable of accurate determinations of gravity in a remarkably short interval of time. This type of instrument would, therefore, seem to be particular-

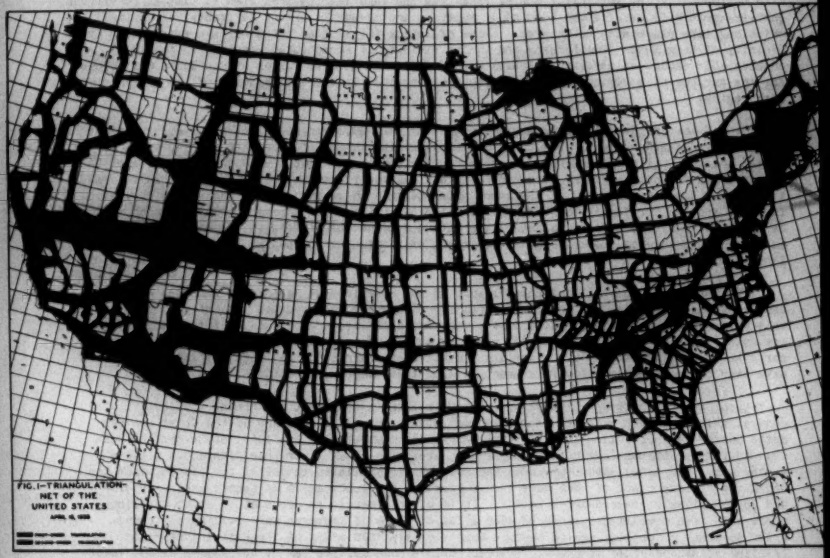

FIG. 1—TRIANGULATION NET OF THE UNITED STATES

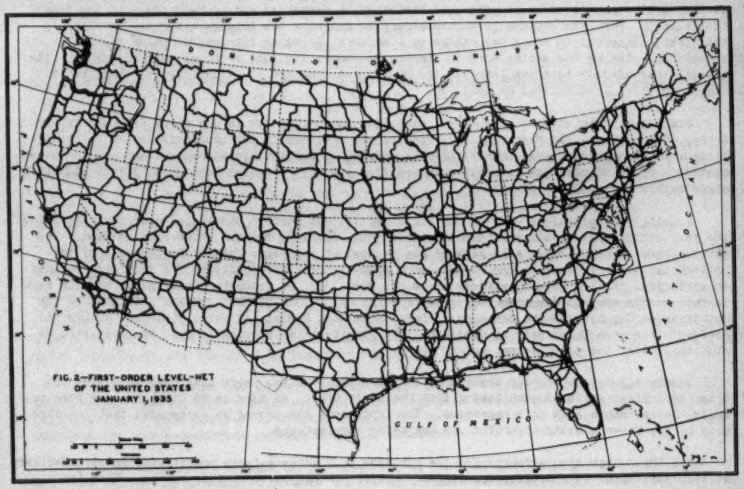

FIG. 2—FIRST-ORDER LEVEL-NET OF THE UNITED STATES JANUARY 1, 1935

ly adapted to obtaining a large number of stations in restricted areas for the purpose of developing important regions for locating hidden geological structure or to profile in greater detail erratic anomalies as obtained by older observations. The operation of this instrument requires that base-stations shall be available for purposes of comparison at fairly frequent intervals. With over 700 gravity-stations now in the United States and outlying islands, such comparison-stations are available in most areas.

Publication of data--It is obvious that the value of control-data to the public making use of them is directly in proportion to the availability of such information in a form readily adaptable for distribution. It is necessary that these data be published as early as practicable after completion if they are to be of maximum value. During the past year the Coast and Geodetic Survey has published a number of volumes both on triangulation and leveling in the various states. It is hoped that within the next year even greater progress will be made along these lines. The present program plans for the publication of such data for each state. The horizontal and vertical control-data are generally published in separate volumes.

The following special publications have either been issued during the past year or are now in press:

No. 181--Leveling in Massachusetts, Rhode Island, and Connecticut
No. 182--Leveling in New Hampshire and Vermont
No. 183--First-order triangulation and traverse in Louisiana (1927-datum)
No. 184--Leveling in Maine
No. 185--Leveling in Florida
No. 186--Triangulation in Missouri (1927-datum)
No. 187--First-order triangulation and traverse in Arkansas (1927-datum)
No. 188--Leveling in Arkansas
No. 189--Triangulation in Texas (1927-datum)
No. 190--Triangulation in Oklahoma (1927-datum)
No. 192--First- and second-order triangulation and traverse in North Carolina (1927-datum)
No. 193--Manual of plane coordinate computations
No. 194--Manual of traverse computation on the Lambert grid
No. 195--Manual of traverse computation on the transverse Mercator grid

For all first- and second-order work it is obvious that accurate and reliable instruments are one of the first requisites. The Coast and Geodetic Survey has been embarrassed in obtaining the desired type of instruments in this country, for the demand has not been sufficient to encourage manufacturers in producing them except on individual contracts. The problem of obtaining accurate graduations of theodolite circles has been a very acute one and it is only within the last year or two that the Survey has been able to equip all of its field-instruments with high-precision circles. This has been made possible through cooperation with the National Bureau of Standards. That Bureau has furnished within the last 12 months 35 very excellent first- and second-order theodolite circles. It has also assisted with the vast amount of work involved in the calibration and standardization of invar tapes and invar strips for first-order level-rods, and in the calibration and testing of various other instruments as required for our field-work.

Office computations--The addition of such an amount of both horizontal and vertical control to the national net has increased the office work tremendously. The office personnel has been greatly augmented so that incoming field-records may be checked and adjusted preparatory to assembling the data in published form as early as possible. Altogether a force of some 300 people are now engaged in this work alone.

The added interest being taken in all classes of geodetic work throughout the country is a very wholesome indication of a greater appreciation by the public generally of the many advantages it furnishes. From an engineering standpoint it is indispensable in furnishing data for irrigation, drainage, flood-control, power, highway, railroad, and general survey-problems. From a scientific standpoint, it furnishes much valuable data for determining the size and shape of the Earth, in locating hidden structures in the Earth's crust,and in revealing movements of the Earth's crust caused by earthquakes or other disturbances. Therefore, geodetic work presents a fertile field for assembling data and determining facts which are essential for the planning required for the conservation of our natural resources and for studying those problems dealing with the physical sciences which will enrich our knowledge of the Earth.

U. S. Coast and Geodetic Survey,
Washington, D. C.

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AMERICAN GEOPHYSICAL UNION

Sixteenth Annual Meeting

SECTION OF SEISMOLOGY

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A THREE-COMPONENT PORTABLE SEISMOMETER DESIGNED FOR THE EVALUATION OF GROUND-MOTIONS

L. B. Slichter

(Abstract)

The seismometers described are of the mechanical type--period two to three seconds--with electromagnetic damping, using high mechanical magnification of the excellent "bow-string" type introduced by Gordon Taylor, and optical registration. Special film of high resolving power and great latitude, and a simple and efficient optical system enable an unusually fine trace to be obtained, readable to about one-thousandth inch if desired. The vertical instrument incorporates La Coste's recent suggestions. Very high static magnifications (over 100,000) are obtainable so that the practical limitations in sensitivity are imposed by the unavoidable background disturbances. Provision for the automatic testing of the instrumental constants is incorporated in the design.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

SUBSURFACE EXPLORATION BY EARTH-RESISTIVITY AND SEISMIC METHODS

E. R. Shepard

Introduction

During the past two years the Bureau of Public Roads has experimented with two geophysical methods of subsurface exploration, with the expectation that they will prove of value in foundation-exploration, in the location of gravel-deposits and other surfacing material, and even as an aid to classifying excavation in highway construction. One of these methods of test--the electrical resistivity-method--has been used for some years with varying degrees of success by several State highway organizations in connection with grading operations, fills through swamps, and for determining the location and extent of suitable gravel-deposits and quarry-material. The other method--the seismic method--although used extensively for locating salt-domes and other oil-bearing structures and in certain types of mining operations, has not been generally applied to shallow determinations. However, tests by the Bureau of Public Roads over a period of several months on known formations around Washington indicate that, for determining the presence and location of consolidated rock, this method is more reliable and accurate and in other ways superior to the resistivity-method.

These and other scientific methods of subsurface exploration are not new to the geophysicist. For many years the magnetometer has been employed in the location of mineral deposits. The Eötvös torsion-balance, a gravimetric instrument, was introduced into this country from Germany about 1922 and, through its use, many salt-domes rich in oil and sulphur were discovered in the Gulf Coast Region.

More recently the seismic method of exploration has come into use and is now the most popular and widely used of all geophysical methods for deep exploration-work. Various electrical methods of exploration are also in use, of which the resistivity-method is finding much favor where relatively shallow determinations are involved.

The electrical resistivity-method

In employing the resistivity-method of exploration the most common procedure is to introduce an electric current of known strength into the Earth through suitably placed electrodes and by means of intermediate electrodes to measure the average resistivity of a volume of earth comparable in dimensions to the electrode-spacing. By progressively increasing the electrode-spacing and repeating the measurements a curve is established which shows the relation of resistivity to depth.

Calculated values of resistivity are plotted as ordinates and corresponding values of electrode-spacing as abscissae. An upward trend of the curve indicates increasing resistivity with depth and suggests the presence of rock, gravel, or some other high-resistance material, while a flat or descending curve is indicative of soil or clay. An abrupt change in curvature indicates a change in material at a depth approximately equal to the electrode-spacing at which the change occurs.

Studies of this kind have been reported by the Bureau of Mines [see references 1, 2, 3, 4 under bibliography], by Schappler and Farnham [5] of the Missouri State Highway Commission, by Kurtenacher [6, 7] of the Wisconsin Highway Commission, by Wilcox [8] of the Minnesota Department of Highways, and by numerous other investigators. Schappler and Farnham were successful in preclassifying excavation-materials on highway projects but had difficulty in interpreting bridge-sounding data due to the fact that coarse sand and gravel overlying the bed-rock possessed a resistivity not markedly different from that of the solid rock. Kurtenacher reported success in the determination of the thickness of stripping on quarries, the location of buried gravel-deposits and the determination of depths to solid bottom in marshes and swamps. Wilcox has confined his work largely to locating shallow deposits of sand and gravel for road surfacing.

The following quotation from the report of Schappler and Farnham shows that in 1931, without the aid of resistivity-measurements, an error of 12.92 per cent was made in estimating the amount of solid rock-excavation in a number of highway projects, while in 1932, on a like number of similar projects on which estimates were based on resistivity-tests, the error was only 1.04 per cent. This comparison suggests the possibility of greatly improving the accuracy of estimates of grading costs on highway projects through the use of this or other methods of preliminary exploration:

"Up to date final estimates have been filed on 25 projects completed in 1932, on which geologists had made reports and preclassified the excavation. The projects were matched as nearly as possible with projects completed in 1931. On the basis of this comparison it was found that the present scheme of preclassifying predicted that 8.32 per cent of all the excavation-quantities would be solid rock, whereas final estimates consider 9.36 per cent of the excavation as solid rock--an overrun of 1.04 per cent. In 1931 preliminary classification predicted 21.79 per cent solid rock whereas final classification gave 8.87 per cent or an underrun of 12.92 per cent. Limiting this comparison to fifteen projects typical of the more difficult area--the Ozark region--in 1932 final classification overran the predictions 3.13 per cent, while in 1931 there occurred an underrun of 24.44 per cent. Although this analysis is far from complete, it does express the general results of this method of preclassifying excavation-materials. Predictions are more nearly accurate than formerly and instead of the tendency to greatly overclassify the solid rock the present trend is toward slightly underclassifying."

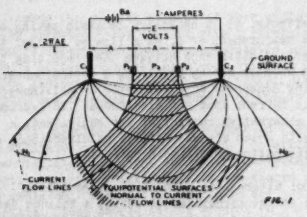
The principle involved in making earth-resistivity measurements is illustrated in Figure 1. An electric current I is caused to flow through the Earth between two electrodes, C_1 and C_2. Measurement is then made of the potential-drop E between two intermediate electrodes, P_1 and P_2, placed in line with C_1 and C_2 and dividing the distance C_1 to C_2 into three equal parts, A, termed the electrode-spacing.

In 1915 Wenner [9] showed that with this four-electrode arrangement the specific resistivity of a homogeneous medium is given by the equation

$$\rho = 2\pi AE/I \qquad (1)$$

where A is expressed in cm. The specific resistivity, ρ is expressed in ohm-centimeters and denotes the resistance in ohms between parallel faces of a centimeter cube of the material. Where A is measured in feet we may write

$$\rho = 191\ A(E/I) \qquad (2)$$



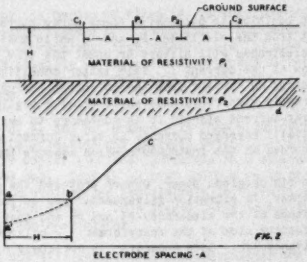


FIG. 1—DIAGRAM FOR THEORY OF EARTH-RESISTIVITY MEASUREMENTS
FIG. 2—TYPICAL RESISTIVITY-CURVE

If the medium is not homogeneous the indicated resistivity, , represents an average specific resistivity of the material bounded by the equipotential surfaces P_1N_1 and P_2N_2 but its value is determined largely by the properties of the material near the surface and only slightly by the material at a relatively great depth. The experience of numerous investigators is rather consistent in showing that for practical depth-determinations the materials within a depth equal to the electrode-spacing, A, largely determine the value of , and that materials at a depth greater than A have a negligible influence on the value of

Let us assume in Figure 2 that a homogeneous soil of resistivity $_1$ exists to a depth H and that below the horizon H a material of greater resistivity $_2$ exists. If, under this condition, earth-resistivity measurements are made with different values of electrode-spacing A, as indicated in Figure 1, and a curve is plotted showing the relation of to A, as in Figure 2, we find that for values of A less than H the curve ab is approximately flat, but when A begins to exceed H the influence of the deeper material begins to affect the value and the curve assumes an upward trend as at b. Rather abrupt changes of this kind are often obtained in practice which afford a means of roughly determining the depth to a change in material. This is indeed a simple empirical rule but one for which there is no theoretical basis. Tagg [10] and others have shown that from theoretical considerations the curve in Figure 2 should assume some such form as a'bcd with no sharp breaks or inflections. In practice, however, and especially on shallow work, rather sharp inflections are frequently obtained where materials of different resistivities are concerned, and these inflections afford a simple and satisfactory means of ascertaining the approximate depth at which the change in material occurs.

Perhaps a more common occurrence is a U-shaped curve in which the electrode-spacing at the low point is taken as the depth to a change in material. The descending branch of the curve is characteristic of many soils in which a decreasing resistivity occurs with depth. Under such conditions an underlying strata of rock or gravel is indicated quite accurately by the low point of the curve.

Selection of type of instrument for earth-resistivity measurements

Three types of instruments are being employed for earth-resistivity measurements, each of which has its advantages and disadvantages. As the men who are often called upon to do this class of work are more likely to have had technical training in geology or civil engineering than in the electrical science, it will be appropriate to discuss the several methods and instruments currently employed, in order that the most suitable arrangement of apparatus may be selected to meet any particular set of requirements. Before discussing the instruments themselves, it will be well to consider certain inherent difficulties which are encountered in earth-resistivity measurements.

The measurements indicated in Figure 1 are not as simple as they are here made to appear. Several sources of stray currents and potentials are likely to exist which must be either eliminated or compensated for if an accurate determination of E, the potential-drop in the Earth between P_1 and P_2, resulting from the current I, is to be obtained. These are: (1) Self potentials originating in local mineral deposits; (2) natural earth-currents of large scope but not often of troublesome magnitude; (3) local stray currents originating from street-railway systems, grounded power-circuits, or mine-railways--these are usually variable in character and are especially troublesome near large city-railway systems or interurban electric lines; (4) galvanic and polarization potentials between electrodes P_1 and P_2; (5) galvanic potentials originating from cinders, coke, or filled ground containing bits of metal or other foreign materials.

In addition to overcoming these stray-current effects, it is necessary to avoid taking any current from the electrodes P_1 and P_2 while making a measurement of E, as a flow of current through these electrodes will distort or upset the true potential-difference between them resulting from the flow of the current I. This latter condition is usually met by employing a potentiometer, which draws no current from the potential-source being measured, or a voltmeter or galvanometer of extremely high resistance which draws a negligible current from the electrodes. To overcome the stray-current effects it is customary to employ alternating current or its equivalent, a periodically reversed current, as stray-current effects which are essentially unidirectional are not recorded on the instruments which measure the alternating or periodic current.

In his original paper, Wenner proposed the use of alternating current supplied from a transformer. A vibration-galvanometer was so placed in the circuit as to detect a balance between the voltage at the electrodes P_1 and P_2 and that on a measured length of slide-wire supplied from the secondary side of the transformer. A balance was indicated when no current flowed through the galvanometer. Such apparatus is obviously not suited to rapid field-measurements.

The first practical application of the four-electrode method of measuring earth-resistivity was made by McCollum [11] of the National Bureau of Standards and applied to the study of stray-current electrolysis on underground pipes and cable-systems. The McCollum earth-current meter embodies a dry battery, a milliammeter, a double commutator, and a voltmeter having a resistance of one million ohms per volt. Current, after passing from the battery through the milliammeter, is commutated at a frequency of about 30 cycles per second and then conducted to the two current-electrodes. This periodic current establishes a potential-difference of the same frequency between two potential-electrodes. Leads from the potential-electrodes are carried to a second commutator mounted on the same shaft with the current-commutator and in phase with it. The effect of this second commutator is to rectify the periodic potential, after which it is measured on the direct-current, high-resistance voltmeter. It will readily be seen that any direct stray-current which may exist in the Earth should not affect the direct-current voltmeter because of having first passed through the potential-commutator.

A set of four electrodes mounted on a frame as a unit, with a 3-inch interval, is commonly employed with the earth-current meter in the study of stray-current electrolysis. Although this instrument is extensively used on electrolysis-work, it apparently has not found application to geophysical prospecting or exploration. There is no reason, however, why it should not be used for this purpose and it might prove particularly suited to shallow determinations.

Gish [12] of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington modified the McCollum earth-current meter and measured the resistivity of large volumes of earth. His instrument embodied a larger and more accurate commutator than that employed by McCollum and he substituted a potentiometer for the high-resistance voltmeter. He also introduced a condenser into the potential-circuit to block the passage of galvanic and stray direct-currents from the ground to the potentiometer, and reduced leakage between the current and the potential-circuit by the addition of a guard-ring. This type of apparatus has been used quite extensively for geophysical explorations during recent years.

Another instrument, known commercially as the "Megger" [2], was designed primarily to measure the resistance of driven and buried grounds for power-stations and electric circuits but is also employed successfully under certain favorable conditions for subsurface exploration. It embodies a hand-driven direct-current generator, a double commutator on the same shaft with the generator, and a single indicating instrument known as an ohm-meter. By a special arrangement of the coils and magnetic circuit this meter is made to register the ratio E/I and to thus indicate ohms directly. The fact that this instrument must of necessity draw current from the potential-electrodes is distinctly to its disadvantage. The error, however, is not serious in moderate depth-determinations if the contact-resistance of the potential-electrodes is kept reasonably low. This sometimes necessitates the use of water and rather long potential-stakes. If accurate values of resistivity are desired, it is necessary to measure the resistance of each potential-stake to ground and to compute certain correction-factors based on these measured resistances.

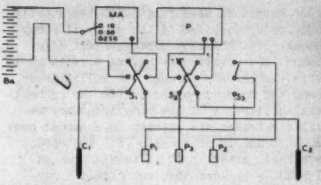
Eve, Keys, and Lee [2] of the Bureau of Mines have shown that comparative values of resistivity as obtained with the "Megger" are often subject to the same interpretations as are similar data obtained by more precise methods. An improved "Megger," designed especially for geophysical work, and embodying a potentiometer, is said to be now available.

Method employed by Bureau of Public Roads

Among the several methods of test employed by the Bureau of Mines [4] is that embodying a simple direct-current circuit with a reversing switch instead of a commutator. Non-polarizable potential-electrodes are also substituted for the conventional iron stakes. Lee [1] also introduced a center potential-electrode by which it is possible to determine underground-slopes by making independent measurements on either side of the center. This type of apparatus is the one adopted and employed by the Bureau of Public Roads.

Its essential features are shown in Figures 3, 4, and 5. Figure 4 is from a photograph of the apparatus as used in the field. To minimize polarization and galvanic potentials, special potential-electrodes are employed, consisting of a copper-electrode submerged in a concentrated solution of copper-sulphate in a non-glazed porous cup. Cups 10 cm high and 5.2 cm in diameter are employed. When not in use these are kept in an earthen jar containing a solution of copper-sulphate. They should not be brought in contact with metals. Iron stakes 1-1/4 inches in diameter and about two feet long are used for current-electrodes.

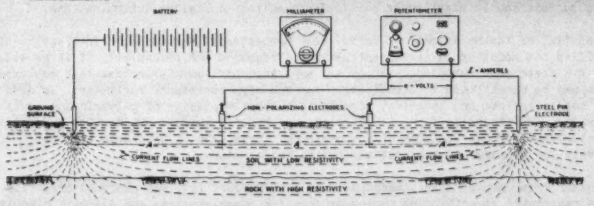
A milliammeter having ranges of 10, 50, and 250 milliamperes and a potentiometer are mounted on a 12-inch by 21-inch oak board, together with the necessary switching arrangements shown



Ba - 220 VOLT "B" BATTERY. MA - MILLIAMMETER.
C1 & C2 - CURRENT STAKES. P - POTENTIOMETER.
P1, P2 & P3 - NON-POLARIZING POTENTIAL ELECTRODES.
S1 - REVERSING SWITCH TO CHANGE DIRECTION OF CURRENT THROUGH GROUND.
S2 - REVERSING SWITCH TO POTENTIOMETER TERMINALS.
S3 - SWITCH TO CONNECT P1 & P3 OR P2 & P3 TO POTENTIOMETER

FIG. 3—CIRCUIT-DIAGRAM FOR EARTH-RESISTIVITY MEASUREMENTS

FIG. 4—DETERMINING DEPTH TO ROCK BY MEASURING EARTH-RESISTIVITY



BASIC RESISTIVITY FORMULA

$$R = \frac{2\pi A e}{I}$$

IN WHICH:—
R = SOIL RESISTIVITY
A = DISTANCE BETWEEN ELECTRODES IN CENTIMETERS
e = DIFFERENCE IN POTENTIAL BETWEEN INTERMEDIATE ELECTRODES IN VOLTS
I = CURRENT FLOWING BETWEEN END ELECTRODES IN AMPERES

TYPICAL RESISTIVITY CURVE

AS THE DISTANCE A IS PROGRESSIVELY INCREASED, THE DEPTH OF THE CURRENT PENETRATION INTO THE SOIL IS INCREASED, AND USUALLY THE RESISTIVITY OF THE SOIL DECREASES WITH THE GREATER CONDUCTION AT GREATER DEPTHS. FINALLY A NUMBER OF CURRENT FLOW LINES ENCOUNTER ROCK AND THE RESISTIVITY CURVE TAKES AN UPWARD DIRECTION BECAUSE OF THE HIGH RESISTIVITY OF THE ROCK. GENERALLY THE DEPTH OF THE ROCK BENEATH THE GROUND SURFACE IS EQUAL TO TODAY VALUE OF A AT WHICH THE UPWARD TREND OF THE CURVE BEGINS.

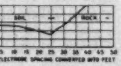
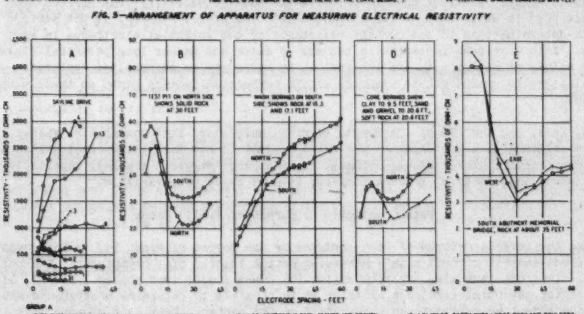


FIG. 5—ARRANGEMENT OF APPARATUS FOR MEASURING ELECTRICAL RESISTIVITY


A
SKYLINE DRIVE
B
TEST PIT ON NORTH SIDE SHOWS SOLID ROCK AT 30 FEET
C
MAIN BORINGS ON SOUTH SIDE SHOWS ROCK AT 15.3 AND 17.1 FEET
D
CORE BORINGS SHOW CLAY TO 9.5 FEET, SAND AND GRAVEL TO 20.6 FT., SOFT ROCK AT 20.6 FEET
E
SOUTH ABUTMENT MEMORIAL BRIDGE, ROCK AT ABOUT 25 FEET
RESISTIVITY - THOUSANDS OF OHM-CM
ELECTRODE SPACING - FEET
NORTH
SOUTH
EAST
WEST

GROUP A
1 - GAPE ENTRANCE AT PANORAMA, EARTH AND SMALL STONES
2 - 0.267 MILES, STONY SOIL
3 - 0.506 MILES, IN GUTTER AT HEAVY ROCK CUT
4 - 1.615 MILES, CONTINUOUS ROCK, SEAMED AND BROKEN
5 - 1.58 MILES, EARTH BANK WITH STRATUM OF BOULDERS AT 10 FEET
6 - 1.805 MILES, SOLID ROCK CUT
10 - 1.91 MILES, EARTH WITH LOOSE ROCK AND BOULDERS
13 - 3.04 MILES, ROCK CUT
21 - SOUTH OF PANORAMA, EARTH

FIG. 6—RESULTS OF EARTH-RESISTIVITY MEASUREMENTS

in Figure 3. The ammeter is elevated to the same level as the face of the potentiometer and the switches are installed on the vertical front of its support. Leads of No. 18 lamp cord are used. These are wound on four brass spools which are mounted on a 9-inch by 12-inch board. This unit is provided with a flat bayonet-attachment by which it is mounted on the back of the instrument-unit when in operation. Another unit containing the necessary batteries and two folding camp-stools complete the equipment. The battery-box provides for nine "B" batteries, of 22-1/2 volts each, with additional space for tape-lines, connecting leads, and porous cups. Two leads connect the battery to the instrument and a dial-switch on the top of the battery-box en-

ables any number of the units to be connected in circuit. Plugs and jacks are used to connect the lead-terminals and the battery to the instrument and small battery-clips are used to connect the leads to the ground-electrodes.

To eliminate the effect of any stray ground-current of a constant and unvarying character, readings are taken with the test-current flowing through the ground, first in one direction and then in the other. This is accomplished by the reversing switch, S_1. Potential-drop readings are taken between P_3 and P_1 and between P_3 and P_2 for both directions of current-flow. Four values of current and four values of potential-drop are thus obtained for each electrode-setting, and from these data four values of R, the ratio E/I, are derived. Resistivities are computed by substituting in equation (2) after adding the two values of R obtained on either side of the center. If the two values of R are averaged, then a constant of 382 instead of 191 must be used in equation (2). By repeating these measurements for a series of electrode-spacings, it is possible to construct two resistivity-curves as shown in B, C, D, and E, Figure 6, which apply along the line of test on either side of the center-electrode.

A fairly rapid technique has been developed which enables a crew of two engineers and two helpers to make from 10 to 20 shallow tests per day. By shallow tests is meant those involving such depths as are encountered in highway grading through rough country and requiring from 6 to 20 measurements at each test-location. An electrode-spacing in intervals of three feet, or multiples thereof, has been adopted as standard and both current and potential-stake locations are marked on the plain side of two 100-foot linen-tape lines to conform to a 3-foot interval. Potential-electrode locations are marked by consecutive numbers in red while every third position is marked consecutively in black to indicate current-stake positions. The end links of the two tape-lines are brought together at the center-point of the test and a surveyor's iron pin stuck through them and into the ground. The tape-lines are then run out to their full length in either direction and pinned to the ground in a taut position. With one man to read the instruments, one man to record the data and compute the resistivities with a slide-rule, and two helpers to move the electrodes progressively from point to point, it is possible to run a 60-foot depth-test in from 30 to 40 minutes.

The curves are plotted before moving and any irregularities checked on both paper and ground before leaving the set-up. Sometimes it is desirable to obtain additional points on the curves to establish definitely the points of inflection. By this procedure it is usually possible to obtain fairly smooth and consistent curves. No sharp inflections have been found except at shallow depths. The jagged and pointed curves reported by some investigators at depths of several hundred feet cannot be reconciled with either theory or careful practice.

Some trouble from stray railway-current has been encountered in and near Washington when attempting depth-measurements in excess of about 50 feet. This difficulty can usually be met by using sufficiently large test-currents to mask the effects of the variations in the stray currents and by taking the average of several readings for each electrode-interval. It seems probable, however, that active stray-currents will preclude the use of this method of measurement for depths in excess of 100 to 200 feet. To compensate for this disadvantage there are a number of advantages which make this so-called porous-cup method of test preferable to all others. These include low cost of equipment and high accuracy under a wide range of depths and resistivities.

When working in soils of unusually high resistivity, especially during dry periods, it is sometimes difficult to get enough current through the potential-electrodes to operate the "Megger" and other commutator-devices. Even though a potentiometer is used in the potential-circuit, the small amount of current required to charge the leads is sometimes sufficient to upset the normal potential-relations. The only effect of such a condition when using the porous-cup method is a reduced sensitivity of the potentiometer-galvanometer caused by the high resistance of the circuit. However, as no current is actually drawn from the potential-electrodes, a satisfactory balance is always obtained. The porous cups are placed directly on the ground-surface although leaves, grass, and other trash are usually removed. Unless the soil is dust-dry, no difficulty is encountered in obtaining satisfactory readings. With other types of apparatus it is often necessary to water the electrodes or drive them to a considerable depth. One case is reported where potential-stakes 12 feet in length were used in connection with "Megger" tests.

The paper and slide-rule work involved in the porous-cup method is somewhat greater than with other methods of test because of the necessity for making four sets of observations for each electrode-interval. With the Gish-Rooney apparatus only two sets of readings are necessary, while with the "Megger" no division-operations are required as the instruments indicate ohms directly. It is necessary, however, to multiply the "Megger" readings by a constant and by the electrode-spacing to obtain actual resistivity-values.

As to weight and portability, the "Megger" and the earth-current meter are about on a par and considerably lighter than either the Gish-Rooney or the porous-cup apparatus. None of the instruments requires very accurate leveling. The Gish-Rooney apparatus is scientifically more accurate than any of the others and will perhaps yield satisfactory data over a greater variety of conditions than the others. For the relatively shallow depths encountered in highway construction, as well as for deeper determinations where stray-current disturbances are absent, the porous-cup apparatus appears to be entirely satisfactory and is favored because of its low cost and its simplicity of construction and operation.

Results of experimental studies of earth-resistivity

Resistivity-measurements carried out by the Bureau of Public Roads have been confined largely to experimental studies on known formations for the purpose of developing suitable apparatus and methods of test and to determine under what conditions this method of exploration may be of value on highway and bridge-construction projects. Army engineers have made many borings in and about Washington in connection with bridge-construction and other structures and these data afforded an excellent opportunity to check resistivity-tests against the logs of these borings. A period of several weeks was also spent along the projected route of the Sky Line Drive in the Shenandoah National Park, on both graded and ungraded sections. Preliminary measurements were made opposite cuts along graded sections prior to working along sections where grading was soon to begin. Part of the route on which measurements were made was examined after the grading had been completed and comparisons made between the field-notes and the exposed cuts. Figure 6 shows a very few of the many resistivity-curves obtained. The curves in group A were all made along graded sections of the Sky Line Drive, while curves B, C, D, and E were obtained near Washington. In group A only one of the two curves obtained at each location is shown.

Perhaps the most significant feature brought out by these studies is the wide range of resistivities in both soil and rock encountered within a comparatively limited area and the entire lack of uniformity and regularity in the upper layers of the Earth's crust. Soil-resistivities often vary enormously from hill to hill, and adjacent mountains may exhibit distinctly different characteristics with respect to soil and rock. Igneous intrusions, sedimentation, erosion, faulting, weathering, folding, and other geologic forces have contributed to make the Earth's surface so erratic and irregular in its composition that no systematic continuity of materials is to be found, especially in rough or mountainous areas. Because of these conditions, the interpretation of resistivity-measurements is often indefinite or uncertain and frequent correlations with known conditions should be made wherever possible.

Reference to Figure 6 will show the enormous range in resistivities encountered within the space of a few miles along the Sky Line Drive. In spite of this wide range in resistivity the shape of the curve can usually be depended upon to indicate the character of the underlying material. A flat or drooping curve such as 31, 1, 10, 2, and 5 usually indicates earth or loose rock, while ascending curves such as 6, 3, 13, and 4 indicate the presence of rock. Near Front Royal, Virginia, some 20 miles north of Panorama, resistivity-values for both soil and rock are much lower than those shown in Figure 6. Earth-resistivity as low as 6000 ohm-cm was found at an elevation of 1000 feet as against values of 100,000 to 400,000 ohm-cm near Panorama at an elevation of more than 2000 feet.

Rock-resistivity was also found to vary over wide limits, and in one location was so low as to fail to give indications of its presence. Although not all of the ten miles of right-of-way explored has been examined subsequent to grading, enough has been checked to prove that such tests should provide highly valuable information to bidders and contractors.

Precise classification cannot be expected but it should be possible to identify two and possibly three kinds of material, such as earth, broken or loose rock, and consolidated rock. After all, the contractor is primarily interested in knowing if he can handle the material with his shovel or whether he will be required to resort to blasting. The resistivity-test can give him the answer in the great majority of cases.

Curves B, C, D, and E were made in an area near Washington where rock-depths had been determined by a large number of test-pits and borings. Curves B and D are typical of most of the area where good checks were obtained by taking the electrode-spacing at the lowest point on the curve as the depth to rock. However, in a few instances curves like those shown in C were obtained. In such locations the relative resistivities of the different strata are such as to obscure the location of the rock. Curve E was obtained at the south abutment of the Arlington Memorial Bridge where the bed-rock is known to be about 35 feet from the surface. Although there is undoubtedly a great difference between the resistivity of the overlying muck and that of the rock, the sharp inflection in these curves is somewhat surprising and in strong contrast

with other measurements along the Potomac River where positive identification of the rock at depths of from 40 to 70 feet has not been possible. As the inflection occurs in both the east and the west curves, it cannot logically be attributed to local surface-conditions near the current-stakes.

Resistivity about a single electrode

The single electrode-method of measuring earth-resistivity, which has found favor with some investigators, is illustrated in Figure 7. If a current, I, is made to flow through the earth between electrodes C_1 and C_2, we may assume that the flow of current from C_1 into a homogeneous soil will be radial if C_2 is at a comparatively great distance from C_1. With a radial flow of current from C_1 we can express the resistivity of the medium by the equation

$$\rho = 191\ (E/I)[r_1 r_2/(r_2 - r_1)] \qquad (3)$$

where E is the potential-drop between the two equipotential, hemispherical shells P_1 P_3 and P_2 P_4, and r_1 and r_2 are expressed in feet. The material for which ρ is obtained is that enveloped between the two concentric shells and designated by shading in Figure 7. By progressively increasing r_1 and r_2 and measuring the potential-drop, P_1 P_2 or P_3 P_4, a curve is obtained showing the relation of ρ to r_2. This curve will be similar to that obtained by the four-electrode method and is supposed to indicate changes in material in the same manner, since the material included in the test has a depth equal to r_2.

As r_1 and r_2 are increased, the equipotential shells deviate more and more from a true hemisphere because the current-stake C_2 is not at an infinite distance from C_1. The error introduced by the dissymmetry of the electric field about C_1 is shown in the curves in Figure 8 and is seen to be greater in the direction toward C_2 than away from it. For this reason it is preferable to make potential-difference measurements at P_3 P_4 rather than at P_1 P_2

One advantage which has been claimed for this method of test is that the current-stakes remain fixed during any depth-test and therefore the results are not subject to the influence of local surface-variations near the current-stakes, as may occur with the four-electrode method. The Bureau of Public Roads has not experimented with this method to any great extent but in the few comparative tests which have been made between the two methods, the four-electrode method was found to give the smoother and more consistent curves.

The seismic method of subsurface exploration

In employing the seismic method of exploration advantage is taken of the wide difference in the acoustical properties of plastic and granular matter on the one hand and rigid or consolidated matter on the other. Non-rigid matter such as sand, clay, or gravel transmits wave-disturbances, commonly called sound-waves, at velocities of 1000 to 6000 feet per second, while rigid materials like rock or crystalline matter transmit such disturbances at 16,000 to 20,000 feet per second. Here, then, we have a means of measuring directly that property of subsurface materials with which the engineer is concerned, namely, rigidity, while the resistivity-method attempts to measure this property indirectly or through its somewhat questionable relation to electrical resistivity. The seismograph is, therefore, more definite in its identification of solid rock than is the resistivity-apparatus but cannot readily distinguish between clay and coarse sand or gravel, as can often be done by the resistivity-method.

In view of the success with which the seismic method of exploration has been applied to oil-prospecting and the fact that it is distinctly the favorite of all geophysical methods, it is somewhat surprising that it has not heretofore been adapted to relatively shallow determinations. Perhaps the reason for this is to be found in the rather formidable array of apparatus and equipment ordinarily required and the cost of such operations as commonly carried out. The Oil and Gas Journal, referring to recently developed seismic reflection equipment for geophysical prospecting, says: "It consists mainly of two separate units, the recording truck and the firing car. The recording truck contains the seismometers or pick-ups (ordinarily 6), the amplifiers, and batteries, wire-reels, the camera, as well as field-telephone, and various other accessories. The firing car contains explosives, firing box, double reel, and telephone for cross-communication with the recording truck. A drilling truck and water car are ordinarily added."

Anyone contemplating this array of cars and equipment might well question its practicability as a substitute for the soil-auger or other relatively simple methods of exploring shallow depths. Such equipment may be justified where the discovery of a new oil-field may mean a matter of millions to the operator but can it be applied efficiently to less important discoveries?

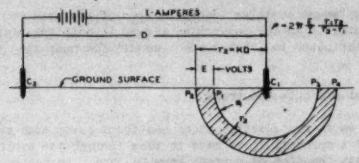


FIG. 7—RESISTIVITY ABOUT A SINGLE ELECTRODE

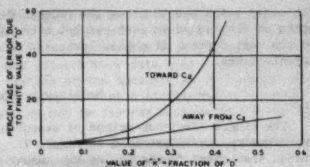
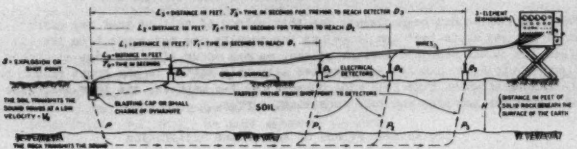


FIG. 9—ERROR IN SINGLE-ELECTRODE METHOD

FIG. 9—ELECTRICAL SEISMOGRAPH SET-UP FOR FIELD-USE


SOIL
SOLID ROCK
ELECTRICAL DETECTORS
GROUND SURFACE
BLASTING CAP OR SMALL CHARGE OF DYNAMITE
THE SOIL TRANSMITS THE SOUND WAVES AT A LOW VELOCITY = V_s
THE ROCK TRANSMITS THE SOUND WAVES AT A HIGH VELOCITY = V_r
DISTANCE IN FEET OF SOLID ROCK BENEATH THE SURFACE OF THE EARTH

TYPICAL PHOTOGRAPHIC TIME RECORD ON MOTION PICTURE FILM

ONE SUBDIVISION = $\frac{1}{100}$ OF A SECOND
TIME OF EXPLOSION
INITIAL SOUND WAVES CAUSED BY THE EXPLOSION REACH THE DETECTORS AT THESE POINTS

DETERMINATION OF DEPTH TO SOLID ROCK = H

$V_s = \frac{L_1}{T_1}$ = VELOCITY OF SOUND WAVES IN SOIL. EQUATION (1)

$T_2 = \frac{L_2}{V_s} - \frac{L_1}{V_s} = \frac{L_2}{V_s} - \frac{L_1}{V_s} = \frac{L_2 - L_1}{V_s}$ EQUATION (2)

$T_3 = \frac{L_3}{V_s} - \frac{L_1}{V_s} = \frac{L_3}{V_s} - \frac{L_1}{V_s} = \frac{L_3 - L_1}{V_s}$ EQUATION (3)

THEREFORE $T_3 - T_2 = \frac{L_3 - L_2}{V_s}$ OR

$V_s = \frac{L_3 - L_2}{T_3 - T_2}$ = VELOCITY OF SOUND WAVES IN ROCK. EQUATION (4)

AND $H = \frac{L_2 T_3}{2} - \frac{L_3 L_2}{2 V_r}$ FROM EQUATION (2)

FIG. 10—SKETCH SHOWING FUNDAMENTAL PRINCIPLES OF SEISMOGRAPHIC METHOD

FIG. 11—WAVE-PRODUCTION IN SEISMIC EXPLORATION

FIG. 12

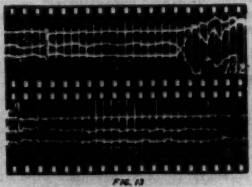


FIG. 13

FIGS. 12, 13, 14—SPECIMEN SEISMIC RECORDS FOR CALCULATION OF DEPTH TO ROCK

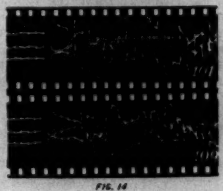


FIG. 14

It was believed that a large part of the equipment required for deep prospecting could be eliminated or greatly simplified in an apparatus designed primarily for relatively shallow work and that a so-called vest-pocket model of the more formidable apparatus could be constructed to meet these requirements. The most important difference between deep and shallow exploration which has made this accomplishment possible is the relatively short shooting-distances involved in the latter. This eliminates the use of telephonic communication between shot-point and recorder as well as most of the cumbersome wire and reels. Only small charges of explosives are required and these can be placed in a 1-1/4 inch soil-auger hole, thus eliminating the heavy drilling equipment required in deep work. The short shooting-distances also permit of less sensitive instruments and the elimination of amplifying equipment with its attending complications.

With these modifications in mind, apparatus was assembled consisting of a three-element oscillograph with camera for photographic recording, three microphonic detectors or pickups, and two 6-1/2 inch spools of wire. Accessories consist of two camp-stools, one 4-foot soil auger, four No. 6 dry-cells or a small storage-battery, one developing tank with developing and fixing solutions, and one changing bag. The whole outfit, together with a crew of three men, can be carried in a small car and can be set up for operation in about ten minutes.

The laborious calculations and involved formulae often employed in deeper determinations can also be dispensed with where shallow structures are concerned, and in their place a simple equation can be substituted, requiring only a mental process or, at most, a slide-rule operation for its solution.

Description of apparatus

The essential units of the apparatus employed are shown in Figures 9 and 10. The detectors seen at the right of Figure 9 are of the microphonic type and consist of four microphone-buttons connected in parallel and mounted with axes vertical. The mica-diaphragms have been replaced with dental-rubber diaphragms which carry polished carbon discs. These lower elements of the buttons are carried on a ring which is integral with a floating inertia-weight in which gravity is balanced by a helical spring about three inches long mounted in the vertical neck of the detector. Lateral alignment is maintained by a thin steel spider-diaphragm and stops limit the vertical movement of the inertia-weight to less than one-sixteenth inch. The upper element of the button consists of a conical carbon-chamber with polished surfaces and containing carbon-granules.

The resistance of this assembly changes enormously with the slightest disturbance, thus making it a detector of exceptionally high sensitivity. While it is subject to some of the inherent defects of the carbon-microphone, it is perhaps the only type of detector which can be used in the field successfully without amplifiers. This feature makes it particularly suited to shallow-exploration work where simplicity and portability are of first importance.

When in operation each detector carries a current of from 5 to 10 milliamperes supplied from dry-cells or a small storage-battery. This current passes through the primary coil of a transformer, the secondary of which is in series with a galvanometer of the oscillograph-type. The galvanometer, therefore, responds only to a change of current in the detector.

The galvanometers are of the coil-type having a direct-current sensitivity of about 4 milliamperes per inch of deflection at 10 inches and an undamped frequency of 1200 cycles per second. The elements, carrying small reflecting mirrors, are damped in oil. An optical system directs light from a 2.5-ampere, 4-volt, straight-filament lamp to the galvanometer-mirror, from where it is reflected and brought to a point-focus in the plane of the photographic film.

Time lines are obtained from "peep-slits" carried on the tines of an electrically driven tuning-fork which vibrates at a normal frequency of 100 cycles per second. The slits, which are one-half inch long and 0.01 inch wide, coincide in the neutral position of the fork and therefore give two lines for each complete cycle of the fork. The timing requires an independent lamp-and-optical system with the exception of the cylindrical lens mounted immediately in front of the film which is common to both light-systems.

The camera used for moving the film is an adaptation of a Sept camera, an obsolete amateur motion-picture camera of French manufacture, which carries a standard 35-mm film. A direct drive was substituted for the intermittent motion and other necessary changes made. A spring-motor drives the film at approximately two feet per second. The film attains its maximum speed almost instantly upon starting the motor, which permits a record to be obtained with a film-consumption of about 18 inches. A numbering lamp and two dials of perforated numbers were installed in the camera, by which it is possible to number films photographically from 0 to 99. This feature

makes it possible to definitely identify records after development. A film-cutter operated by a trigger is provided, by which the film can be cut after any number of shots are taken. As the developing tank accommodates 6 feet of film it is customary to cut the film at every third or fourth shot.

Standard, supersensitive motion-picture film is used as it was found that less sensitive film did not give sufficiently dense traces. Records are developed in a dark-room when convenient or in a Leitz developing tank in the field. A changing bag is needed in transferring the exposed film from the camera to the developing tank.

This equipment, with the exception of the detectors, was built in the shop of the Division of Tests of the Bureau of Public Roads, after purchasing such items as galvanometers, tuning-fork, lenses, and minor electrical supplies.

Methods of determining depths to rock

Two methods of seismic exploration which are in common use are known respectively as reflection-shooting and refraction-shooting. These terms have the same significance in geophysics as they do in optics as the mathematical theory of sound-wave transmission through solids and liquids is based largely on the well-known laws of optics. In reflection-shooting the interpretations are based on waves which are reflected directly from different strata under investigation, while in refraction-shooting it is the refracted waves which are studied. As reflection-shooting is not well adapted to shallow explorations, no further space will be given to a description of that technique.

The principles involved in refraction shooting are illustrated in Figure 11. A blasting-cap or small charge of dynamite is exploded at or under the surface of the ground at some point S, which becomes the center of a wave-disturbance which moves outward on a spherical or near spherical front in all directions. Detectors D_1, D_2, and D_3 placed on a line passing through S pick up this disturbance successively and carry the impulses to three galvanometers which record them as light-traces on a moving photographic film.

By the breaking of a small wire which is wound around the blasting-cap an initial kick or impulse is given to the three galvanometers and the time of the explosion is thereby indicated on all three traces. As the wave-front moves outward from S, its time of arrival at each of the three detectors is indicated on the moving film by disturbances in the traces as shown in Figures 12, 13, and 14. By counting the number of time-units between the initial kick and the arrival of the wave at each detector, it is possible to calculate the average velocity of wave-propagation from shot-point to each detector. From data of this kind it is usually possible to determine with a fair degree of accuracy the depth to the first strata of rigid or consolidated rock and to obtain other information of value regarding the character of the subsurface material.

Referring to Figure 10, the path of the first wave to reach any detector will depend upon the ratio of the shooting distance, L, to the depth to rock, H, and also upon the relative velocities of wave-propagation in the two media. If the shooting distance is relatively short, such as L_1, the path of the first disturbance to reach D_1 will be directly through the soil as indicated. The velocity of the wave through the Earth can then be calculated from the equation

$$V_e = L_1/T_1 \qquad (4)$$

As the shooting distance is increased a point such as D_2 will be reached where the wave first to arrive will no longer be that going directly through the top soil but that taking the path of the refracted wave SPP_2D_2. Subsequent disturbances will reach detector D_2 by various paths, but as only the first arrival can be definitely identified on the film-record it is necessary to base interpretations solely on so-called first events. Likewise, the first wave to reach D_3 will be by the path SPP_3D_3. By measuring the time-difference $(T_3 - T_2)$ and the distance $(L_3 - L_2)$ we are able to calculate the velocity of wave-propagation through the rock from the equation

$$V_r = (L_3 - L_2)/(T_3 - T_2) \qquad (5)$$

This relation is obvious from the fact that the time difference $(T_3 - T_2)$ is taken up by the travel of the wave through the rock from P_2 to P_3, since that part of the path SPP_2 is common to both circuits.

We are now able to write the equation by which H, the depth to rock, can be calculated from known quantities. This is based on the fact that T_3, the total time of travel of the wave from S to D_3, is the sum of the combined times of wave-travel over the path SPP_3D_3. Although refrac-

tion of the wave at the point P is supposed to take place at the angle of total internal refraction, we may assume with negligible error under practical conditions that this angle is 90° and that the distance PP_3 is equal to L_3. With this assumption we may write

$$T_3 = (H/V_e) + (L_3/V_r) + (H/V_e) = (2H/V_e) + (L_3/V_r) \quad (6)$$

or

$$H = (V_e T_3/2) - (V_e L_3/2V_r) \quad (7)$$

When the distance L_3 is of such value that the direct wave through the Earth reaches detector D_3 at the same time as the refracted wave, it is said to be the critical distance and we may write

$$T_3 = (L_3/V_e) = (2H/V_e) + (L_3/V_r)$$

or

$$H = (L_3/2)\,[1 - (V_e/V_r)]$$

and

$$L_3 = 2H/[1 - (V_e/V_r)] \quad (8)$$

For best results, when determining depths to rock, L should not be greatly in excess of the critical distance. As a fairly close approximation we may say that for values of V_e and V_r usually encountered, H = 0.45 L or L = 2.2 H, where L is the critical shooting-distance.

Various modifications of the technique just described are sometimes necessary to determine slopes, domes, and other irregularities in underground-structures. The depth to rock H, as given in equation (7) is really the average of the depth at the shot and that at the detector. By shooting a line of detectors from opposite directions an estimate of the slope can be obtained. Circle shooting is another means of studying subsurface irregularities. This consists in placing two or more detectors on the arc of a circle, the radius of which is greater than the critical distance and the center of which is the shot-point. The order in which the waves reach the detectors will indicate the relative rock-depths under them, the shorter time indicating the shallower rock.

Equation (5) cannot always be relied upon to give very accurate values of V_r because of the difficulty of obtaining an accurate measure of the time-interval $(T_3 - T_2)$ from the film-record. If the detectors are placed 20 feet apart the time-interval representing a velocity of 18,000 feet per second in the underlying rock will be only 0.0011 second, or a distance of about 0.0264 inch on a film moving at a rate of two feet per second. It is obvious that slight differences in the performance of different detectors and errors in picking the exact time of breaks on the traces will make it impossible to determine rock-velocities by the use of closely placed detectors. Fortunately, the term in equation (7), in which V_r appears, is of minor or secondary importance provided the shooting distance is not greatly in excess of the critical distance. For this reason an average or normal value of V_r, such as 18,000 feet per second may be assumed without fear of carrying through an error of any consequence into the final value of H. Equation (7) may be employed only when the shooting distance exceeds the critical distance, and this condition can usually be determined from a measure of the time-intervals between detectors, even though such intervals may not give highly accurate values of rock-velocities.

Results of experimental tests

The accuracy with which H can be determined from equation (7) will depend largely upon the value of V_e selected. In most soils the value of V_e increases with depth and the value to be substituted in the equation must therefore be intermediate between the velocity in the top soil and that in the deeper strata. Figure 15 shows several velocity-distance curves from which values V_e were selected in determining rock-depths at these locations. All of these curves show a distinct upward inflection after the critical shooting-distance is reached or, in other words, when the path of the fastest wave gets into the rock. At the Boundary Channel Bridge the rock is overlaid with about 75 feet of spongy muck or silt and this condition is indicated by the rather flat portion of the curves within the critical distance. The same condition exists at the Bryan Statue Triangle and at the Memorial Bridge, in both locations the critical distance being approximately 100 feet. From the flat portion of such curves fairly accurate values of V_e can be selected and equally accurate values of H obtained.

Figure 11 shows a single record from which the rock depth at the Memorial Bridge can be calculated. The three detectors were spaced respectively 50, 100, and 150 feet from the shot. In this case the critical distance appears to be almost exactly 100 feet. This follows from the

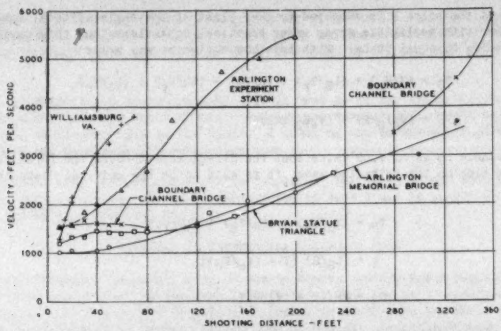


FIG. 13—RELATION BETWEEN VELOCITY OF SOUND-WAVES THROUGH EARTH AS OBTAINED WITH THE ELECTRICAL SEISMOGRAPH

fact that the middle trace shows the same velocity as does the first trace, thus indicating that the wave could have traveled directly through the Earth, but when compared with the third trace the time-interval is such as to give a velocity of 16700 feet per second which is very close to rock-velocity. It is evident, therefore, that the time of travel is the same by either the direct path or the path of the refracted wave through the rock, a condition which determines the critical distance.

Figure 12 shows records from which the depth to rock at the Boundary Channel Bridge was calculated as 76 feet, a figure which checks closely with the bridge-engineer's data.

Frequently the velocity-curve will take the form shown in the Arlington Farm curve, Figure 14, in which the critical distance is not so evident. The method by which a value of V_e was selected and the depth to rock calculated in this location will be given in detail as a typical example of a practical problem. Figure 13 shows some of the records from which depth-calculations were made, while in Table 1 is given a summary of all data obtained. An examination of Table 1 will show that high differential velocities were obtained for shooting distances in excess of 50 feet. Because of the very short time-intervals involved and the difficulty in picking the exact breaking-points on the traces and also as a result of slightly different sensitivities and characteristics in detectors, it is not always possible to obtain accurate differential velocities from which rock-velocities can be derived. It is possible, however, as in this case, to determine whether rock-velocities are encountered and also approximately the critical distance.

The high differential velocities for shooting distances in excess of 50 feet enable us to select this value tentatively as the critical distance. By averaging all of the overall velocities for distances of 50 feet and less, a value of 1834 is obtained. This is so close to the value of 1820 derived directly from record No. 101 for a 30-foot distance that the latter was selected as V_e. Since the values of differential velocities shown in Table 1 are not sufficiently consistent to justify a selection of V_r from them, a value of 16,700 is taken as fairly representative of rock-velocity. As pointed out previously, this value enters into only a minor term in the depth-equation and therefore great accuracy is not so necessary in its determination as in that of V_e. With these values of V_e and V_r the value of H was computed for all distances in excess of 50 feet. The results appear in the last column of Table 1, the average of which is 18.22 feet. The actual depth to rock as determined with a soil-auger is 19.8 feet.

Sometimes it is necessary to make a first approximation of the depth to rock, after which a more accurate value of V_e can be selected from the velocity-curve. In any event, no great error will be made in selecting a value of V_e which is an average of all values obtained under the critical distance.

The velocity-curve obtained at Williamsburg, Virginia, Figure 14, applies to a marl-and-shell conglomerate overlaid by a few feet of clay. These relatively high-velocity values in the absence of rock and within shallow distances are the result of the highly compacted shell-conglomerate which appears to have about the same acoustical properties as a deep clay or shale.

A few tests have been made at quarry-sites and at other locations where solid rock is found within a few feet of the ground-surface and all indicate that the depth of such overburdens can be determined quickly, definitely, and accurately by the seismic method. For such work a single No. 8 blasting-cap gives ample energy, thus reducing the cost of explosives to a negligible amount.

Table 1--Arlington Farm data

Record No.	Shooting distance, L	Time of wave-travel, T	Overall velocity, V	Differential velocity from equation (5)		Depth to rock, H from equa. (7)
	feet	sec	ft/sec	feet	ft/sec	feet
97	10	0.0065	1540	10 to 20 =	1540	....
99	20	0.013	1540	20 to 30 =	2860	....
101	30	0.0165	1820	30 to 40 =	2860	....
104	40	0.02	2000	40 to 50 =	5000	....
106	50	0.022	2270	50 to 60 =	20000	....
107	60	0.0225	2670	60 to 100 =	8900	17.2
100	100	0.027	3700	100 to 120 =	Infinite	19.2
109	120	0.0255	4700	100 to 150 =	25000	16.7
109	150	0.029	5000	100 to 180 =	10700	18.2
109	180	0.0325	5450	60 to 180 =	12000	19.8
			Average			18.22

While our work with the seismograph has been largely experimental and limited to one locality, the results to date have been so promising as to leave little doubt as to the ultimate value of this tool in the study of subsurface formations.

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SOME CORRELATIONS BETWEEN THE OCCURRENCE OF DEEP- AND SHALLOW-FOCUS EARTHQUAKES

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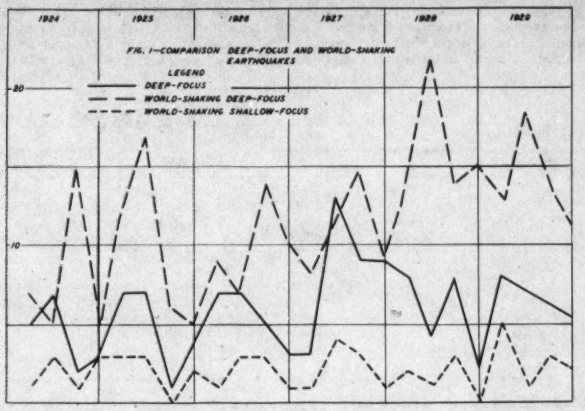
From different sides the attempt has been made to get more information on the occurrence of earthquakes in general by examining the deep-focus earthquakes. These quakes seem to be different from ordinary ones not only in their depth but also in their primary reasons. It has been shown that there exists a periodicity of these quakes corresponding to the pole shift (V. Conrad,



Beitr. Geophysik, v. 40, pp. 113-133, 1933; H. Landsberg, ibid., v. 40, pp. 238-243, 1933). The hypothesis has been forwarded that we have to attribute those quakes to some kind of volume-change to restore physico-chemical equilibrium. If that holds true, an influence on the layers closer to the surface has to be assumed disturbing the mechanical equilibrium there. Therefore, an attempt has been made to find whether there exists any evidence for such an assumption, and only heavy deep-focus earthquakes and severe shallow-focus earthquakes are used for this purpose. Basing on the International Seismological Summary and the Catalog published by V. Conrad (l.c.) we have eliminated aftershocks as well as those quakes which were doubtful as to their coordinates and depth to deal with criticisms by S. W. Visser (S. W. Visser, Beitr. Geophysik, v. 41, pp. 484-486, 1934; V. Conrad, ibid., v. 41, pp. 487-488, 1934).

For 50 selected heavy deep-focus earthquakes the number of severe shallow-focus earthquakes on the three preceding days and the three following days was compiled and in sum found that 21 heavy shallow-quakes happened in the three preceding days, while 40 happened during the three days afterwards. In eight single cases there were more shallow quakes in the three preceding days, in 19 cases more quakes happened afterwards, and in 23 cases the number before and after the deep-focus shock was the same. This result could be interpreted that in some cases the accumulated stresses leading to heavy surface-quakes are precipitated by deep-focus quakes.

More interesting is a survey of longer intervals. The deep-focus quakes for the years 1924 to 1929 were arranged in quarter-years and compared with the number of world-shaking earthquakes during the same period. Thus we get the curves of Figure 1. Curve a represents the total number of deep-focus earthquakes, curve b the number of world-shaking deep-focus quakes, and curve c the number of shallow-focus quakes. If we compute the correlation-coefficients between the curves, we find for a and c 0.186 $\pm$ 0.132 and for b and c -0.05 $\pm$ 0.137 or, in plain words, no evidence of correlation between the two phenomena. However, if we allow a time-lag of one-quarter year for the shallow quakes, which means correlating the deep-focus earthquakes with the world-shaking shallow-focus quakes of one-quarter year later, we get as correlation-coefficients between a and c +0.423 $\pm$ 0.113 and between b and c +0.523 $\pm$ 0.102. In both cases we find a rather remarkable positive correlation. However, I will leave it open whether we are allowed to interpret this fact that an increased activity of severe shallow-focus earthquakes follows one in deep-focus earthquakes.

Another phenomenon is the question of resonance-quakes, namely, one quake is followed by another one in an entirely different region within a short time. This might be attributed either to direct mechanical influence or to a third influence as pole-movements. For this latter theory the papers of Spitaler (R. Spitaler, Beitr. Geophysik, v. 42, pp. 98-109, 1934) are a good support. We present as an example only one table of connection between some heavy deep-focus earthquakes in inner Asia and severe earthquakes in South America. From other inspected material it seems to be possible to prepare similar tables for other regions too.

Table 1--Earthquake-resonance between inner Asia and South America

Date	Character	Location	
		Latitude	Longitude
May 14, 1925	Deep	36.5 N	70.5 E
May 15, 1925	Shallow	25.0 S	71.0 W
June 20, 1925	Deep	37.5 N	72.0 E
June 23, 1925	Deep	0.0	75.0 W
Dec. 25, 1925	Deep	36.8 N	69.5 E
Dec. 25, 1925	Shallow	23.0 S	66.0 W
May 26, 1926	Deep	36.5 N	70.5 E
May 26, 1926	Shallow	14.5 N	88.7 W
July 14, 1927	Shallow	8.8 S	82.3 W
July 15, 1927	Deep	35.0 N	69.0 E
Oct. 2, 1927	Deep	35.0 N	69.0 E
Oct. 2, 1927	Shallow	14.0 N	88.0 W
Jan. 31, 1929	Shallow	12.8 N	91.0 W
Feb. 1, 1929	Deep	36.5 N	70.5 E
Feb. 3, 1929	Shallow	12.8 N	91.0 W
Mar. 1, 1929	Shallow	13.9 N	91.2 W
Mar. 3, 1929	Deep	36.5 N	70.5 E

We present these things as an interesting item without emphasizing any theory too ardently and hope that further investigations along these lines will enlighten this question more completely.

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MOTION OF THE SURFACE OF THE EARTH IN THE COMPRESSIONAL PHASE OF A DEEP-FOCUS EARTHQUAKE, AND THE EFFECTS OF A LAYERED CRUST

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(Abstract)

The early portion of the compressional phase on 28 seismograms of the deep-focus earthquake of November 13, 1932, are integrated to obtain the motion of the surface of the Earth. Comparisons are offered between the observed and actual azimuths of the epicenter at all stations for which two horizontal-component seismograms were available, and between the observed and theoretical apparent angles of emergence for all stations for which three components of motion were available. A test is made of the usual methods of reducing trace-amplitudes, which are based on the assumption that the Earth-motion is sinusoidal. The results of this test indicate that satisfactory estimates of the displacement of the ground corresponding to an impulse on a seismogram can be obtained from the simple harmonic ground-motion assumption, provided the free period of the seismograph is somewhat longer than the duration of the impulse, and provided that the transients in the solution of the equation of motion of the seismograph are retained. Sources of error encountered in any attempt to secure the detailed ground-motion from seismograms are discussed.

An attempt is made to account for the detailed motion of the surface of the Earth during the early portion of the compressional phase on the basis of reflections and transformations of the primary wave within the crust. From the agreement between the predicted and observed composites of horizontal component of motion, certain tentative conclusions are reached: That the oscillatory nature of seismograms is the result of reflections and transformations of primary waves within the crust; that the average thickness of the crust beneath the stations whose records were studied is 32 km; that the velocity-change at the base of the crust takes place within a distance which is small compared to the wave-length.

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THE ELECTRODYNAMIC RATIO OF THE GALITZIN SEISMOMETER

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In his "Vorlesungen über Seismometrie" Galitzin writes the differential equation for the motion of the galvanometer as formula (32) on page 301 in the form

$$\varphi'' + 2\epsilon_1\varphi' + n_1^2\varphi + k\theta' = \theta \qquad (1)$$

where φ represents the deflection of the galvanometer, θ the deflection of the pendulum, and the primes represent differentiation with respect to time. In formula (56) on page 254 he found it convenient to use the quantity defined by

$$h = \epsilon/n \qquad (2)$$

but he does not seem to have been aware of the advantage to be gained in discussing the damping of the galvanometer in terms of the analogous quantity h_1, an advantage that we made capital of in Chapter VIII of our "Introduction to theoretical seismology" (Part II). It did not occur to him, or to any one else for that matter, that the corresponding quantity $k/2n_1$ or $kT_1/4\pi$ might be a much more interesting if not a much more important working constant than his transfer-factor k. Upon examination some interesting relations were obtained, which have led the present writer to the opinion that the choice of k for a working constant was rather unfortunate.

Attention was called to this expression because in the determination of k experimentally $k/2n_1$ is really obtained first, and the transfer-factor k is then computed from it. If we take formula (17) on page 26 of Somville's "Constantes des Sismographes Galitzine," divide through by $2n_1$, and replace the μ with μ^2 so as to return to the usual notation, we have [cf. equation (217) of Introduction to theoretical seismology, Part II]

$$(k/2n_1) = (\varphi_1/\theta_m)(1.4085 + 0.009\mu^2) = (\varphi_2/\theta_m)(3.2305 - 1.098\mu^2) \qquad (3)$$

As will appear in the sequel, there is never any need whatever for knowing the value of k, which we regard as an unimportant function of the other working constants.

The electrodynamic ratio--Let us write for brevity [cf. page 85 of Introduction to theoretical seismology, Part II]

$$Q = 4aFNL_1 \quad \text{and} \quad Q_1 = F_1N_1S_1 \qquad (4)$$

where the quantities on the right have the meaning assigned by Galitzin on pages 286 and 300. (Our Q and Q_1 are not the same as Galitzin's Q and Q_1 on the same pages.) Q and Q_1 are the electrodynamic constants of the pendulum and the galvanometer, respectively. The coefficient of φ' in Galitzin's equation which he has written as $2\epsilon_1$ for short in our equation (1) above, is given in full multiplied by K_1 on page 289; using (4) above this may be rewritten [cf. page 86, Introduction to theoretical seismology, Part II]

$$b_0 + Q_1^2/(R + \rho) = 2\, h_1n_1K_1 \qquad (5)$$

where b_0 is the windage-constant of the galvanometer, K_1 is the moment of inertia of the galvanometer, and $(R + \rho)$ is the total resistance of the circuit. But it is always simpler to describe the damping of the galvanometer in terms of h. If the galvanometer is allowed to swing on open circuit, the resistance is infinite and the second term of the left-hand member of (5) vanishes. If the residual damping with open circuit is given as h_0, then

$$b_0 = 2\, h_0n_1K_1 \qquad (6)$$

so that

$$Q_1^2/(R + \rho) = 2\, n_1K_1(h_1 - h_0) \qquad (7)$$

As h_1 describes the total damping of the galvanometer, and h_0 the mechanical damping, the difference $(h_1 - h_0)$ is the electromagnetic damping and is proportional to the conductance of the circuit. From Galitzin's formula (31) on page 301 we have [cf. equation (133), correcting a misprint of Introduction to theoretical seismology, Part II]

$$K_1k = QQ_1/(R + \rho) \qquad (8)$$

so that dividing (8) by (7) we have

$$Q/Q_1 = k/2n_1(h_1 - h_0) \tag{9}$$

or if we solve for $k/2n_1$

$$k/2n_1 = (h_1 - h_0)Q/Q_1 \tag{10}$$

In actual practice $h_1 = 1$ and h_0 is about 0.03 so that $k/2n_1$ is a good approximation of the ratio of the electrodynamic constant of the pendulum to that of the galvanometer. We may call it the modified electrodynamic ratio or the electrodynamic ratio as affected by the conductance of the circuit. The working constant $k/2n_1$ would seem, therefore, to be much more tangible than the transfer-factor k.

Magnification formulas--The introduction of the modified electrodynamic ratio into the magnification-formula helps considerably toward the appreciation of the physical principles involved. This necessitates a slight regrouping of factors. The actual magnification of the Galitzin seismometer for a simple harmonic earth-motion after the transient term has died away may be written [cf. equation (151) of Introduction to theoretical seismology, Part II, and equation (49) on page 307 of Galitzin's Vorlesungen über Seismometrie]

$$V = kA_1T_e/\pi\ell U_1U = kA_1Tu/\pi\ell U_1U = kA_1T_1u_1/\pi\ell U_1U \tag{11}$$

but the importance of the ratio $k/2n_1$ suggests that it be factored

$$V = (k/2n_1)(A_1/\ell)(4u_1/U_1)(1/U) \tag{12}$$

Here A_1 is the distance from the galvanometer-mirror to drum, and ℓ is the distance from the axis of the pendulum to its center of oscillation. We may assume that the galvanometer is critically damped, and that μ^2 is small, because these are the assumptions under which the constants are determined. Then

$$U_1U/4u_1 = (u_1 + 1/u_1)(1 + u^2)/4 - 1/2\ u\mu^2 \tag{13}$$

so that the regrouping of factors gets us into no trouble. In determining the constants the assumption is also made that T is nearly equal to T_1. If the seismometer is in perfect adjustment $T = T_1$ and $\mu^2 = 0$. Then (cf. equation (155) of Introduction to theoretical seismology, Part II]

$$V_s = kA_1T/4\pi\ell = kA_1\ T_1/4\pi\ell = kA_1/2n_1\ell \tag{14}$$

is the magnification for an earth-motion of the same period as that of the seismometer. If the seismograph is in sufficiently close adjustment for its constants to be determined by the tapping test, the difference between these expressions can be neglected for any practical purpose. On this score the second member of (14) has been called the synchronous magnification in the Georgetown Instrumental Bulletins up to and including June 1934. But it will be seen that the fourth member of the same equation is equally entitled to the same name by the same argument. In Introduction to theoretical seismology, Part II (page 94), the term synchronous magnification is defined only for the case of perfect adjustment. On pages 121, 125, and 126 the former Georgetown practice is proposed, but this practice has been discontinued at Georgetown and is no longer recommended. The synchronous magnification is better taken as the modified electrodynamic ratio multiplied by the ratio of the mirror-drum distance to the reduced pendulum-length. This means that the formulas as given on page 125 of Introduction to theoretical seismology are still used, but the division by T_1 and subsequent multiplication by T are both omitted.

The galvanometric advantage--With these details settled, we can stop to look at some of the formulas from the physical standpoint. If we substitute for $k/2n_1$ its value from equation (10), we obtain

$$V_s = (A_1/\ell)(Q/Q_1)(1 - h_0) \tag{15}$$

This is a very interesting formula. If we neglect h_0 as making an error around 3 per cent and write simply

$$V_s = (A_1/\ell)(Q/Q_1) \tag{16}$$

one would mistake it for the geometrical magnification of a mechanically recording seismometer and would think of the quantities Q and Q_1 as the lengths of multiplying levers. Thus the electrodynamic ratio plays the part of the mechanical advantage of a mechanical system. The stronger the electrodynamic constant of the pendulum and the weaker the electrodynamic constant

of the galvanometer, the greater the magnification. The analogy is not perfect, but it has some value in picturing the behavior of the Galitzin seismometer in terms of an instrument that is easier to understand. Equation (15) shows that the synchronous magnification is also proportional to the conductance of the circuit on account of the factor $(1 - h_0)$, but this was to be expected anyway from physical considerations.

Let us finally suppose that the galvanometer is heavily overdamped. The increase of conductance will drive up the synchronous magnification, but this will be offset by the effect of the damping on U_1. With $h_1 = 10$ and u_1 between 0.2 and 5.0, we shall not have an error exceeding 3 per cent if we write $U_1 = 2h_1u_1$. If we substitute this value in (12), and at the same time substitute the value of $k/2n_1$ from (10), we have after cancellation

$$V = (2A_1/\ell)(Q/Q_1)(1/U)[1 - (h_0/h_1)] \qquad (17)$$

With h_1 about 10 and h_0 about 0.03, the latter can be neglected and we have

$$V = (2A_1/\ell)(Q/Q_1)(1/U) \qquad (18)$$

which would be mistaken for the actual magnification of a direct optically-recording instrument such as the Milne-Shaw. Since this is a comparison of actual magnifications, the analogy is strong. The electrodynamic constants are again playing the parts of levers and the electrodynamic ratio is analogous to a mechanical advantage.

Conclusions--The transfer-factor k is neither important for understanding the principle of the Galitzin seismometer, nor for purpose of computation. The modified electrodynamic ratio or galvanometric advantage, $M = k/2n_1$, is recommended to replace k in theoretical discussions as an intermediate working constant. The magnification-constant should be given as (MA_1/ℓ) which may be written as V_s and may be called the synchronous magnification.

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PROGRESS IN SEISMOLOGY OF UNITED STATES COAST AND GEODETIC SURVEY AND COOPERATING INSTITUTIONS

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The term "cooperating" is so broad that it must be defined for the purposes of this paper. It will include: Those who contribute or have contributed to the actual cost of operation; those who furnish data which are interpreted by the United States Coast and Geodetic Survey; and those who interpret and use data after they have been obtained by the Bureau either directly or through cooperation. The cooperators include educational and scientific institutions, engineering groups, and many others.

As some of the cooperators have to be mentioned frequently, abbreviations will be used for them as follows: CGS for United States Coast and Geodetic Survey; JSA for Jesuit Seismological Association; CIW for Carnegie Institution of Washington--the CIW has an Advisory Committee in Seismology and jointly with California Institute of Technology operates the Seismological Research Laboratory at Pasadena; Cal-Tech for California Institute of Technology (see also last item); UC for University of California; and SRL for Seismological Research Laboratory (see CIW above).

Teleseismic work--Records were obtained at the following stations: CGS at San Juan (Puerto Rico), at Tucson (Arizona), at Sitka (Alaska); Ukiah (California--International Latitude Observatory); CGS and cooperator named at Chicago (Illinois--University of Chicago), at Columbia (South Carolina--University of South Carolina), at Bozeman (Montana--University of Montana), at Honolulu (Hawaii--University of Hawaii), at College (Alaska--Alaska Agricultural College and School of Mines, about to start).

Cooperators furnishing records for interpretations--Technology (near Machias, Maine--Massachusetts Institute of Technology); Burlington (Vermont--University of Vermont); Philadelphia (Pennsylvania--Franklin Institute); Pittsburgh (Pennsylvania--University of Pittsburgh); Charlottesville (Virginia--University of Virginia); Des Moines (Iowa--private station of M. M. Seeburger); Seattle (Washington--University of Washington). There are also the records at Huancayo (Peru--CIW, Department of Terrestrial Magnetism) and Montezuma (Chile--Smithsonian Institution). Interpretations reported by the Panama Canal Station at Balboa Heights are published.

This lengthy list of 17 stations shows what important results are being obtained from this cooperative activity. It should be understood further that there is the closest cooperation of all these groups and others in the country. Records from various stations in one case for a large number have been furnished by the CGS and cooperators to five seismological investigators during the past year. An interesting example of how such cooperation works is in the absence of Professor Jacobs of the University of Vermont for six months' Sabbatical leave. He was somewhat fearful that if he kept his instrument in operation serious instrumental difficulties might develop which could not be handled with facilities at the University. An understanding was reached that in view of the cooperation the CGS would send a competent representative in such event and the station has continued in operation.

Immediate location of earthquake epicenters in cooperation with Science Service and the JSA and many of the above and other stations has continued as heretofore, 33 epicenters being located from April 15, 1934, to April 15, 1935. About six were abnormally deep. The total number of epicenters for the year will run close to 100.

Earthquake information--The arrangements for collecting information regarding earthquakes has continued as heretofore except that in recent years the National Research Council has not been active. The JSA collects information for a region which centers at New Madrid (Missouri). In California and adjacent states there is an adequate cooperative arrangement with many organizations and individuals taking part. In Alaska the Alaska Agricultural College and School of Mines (University of Alaska after July 1, 1935) cooperates in collecting information. In all parts of the country the Weather Bureau continues to furnish many reports. When an earthquake occurs in any part of the country not included in regions having special arrangements, the CGS at once sends out a considerable number of questionnaires to postmasters and others and in general secures quite complete information. In some cases as of an important earthquake, there may be many gaps but usually some individual or organization, or, if there are interesting geological features, the United States or State Geological Surveys, make special examinations and supplement the reports.

This matter of gaps also occurs in California in spite of the elaborate reporting system. The present plan is to plot reporting stations at once on a map and then Professor Byerly of the UC or the SRL advise as to filling of gaps.

On the whole, the plan is quite effective and our knowledge of earthquakes as they occur is far more complete than a few years ago.

The information is made available in various ways but principally in the monthly instrumental reports, which include all CGS and cooperative stations and the annual publication of the CGS, "United States Earthquakes for ____". Non-instrumental information is abstracted and distributed quarterly for the West Coast Region [see reference 1 under references at end of paper]. There are frequent articles on special earthquakes. Publications during year include lists of California earthquakes [2], World distribution of earthquake epicenters [3], and List of seismic seawaves [4].

Recording of strong earthquake-motion--Till recent years and even now in most parts of the Earth, earthquake-study has included only teleseismic observation and analysis and the collection of reports and other information in the region affected by damaging earthquakes. These two rarely overlapped since, in regions with the latter conditions, the instruments were unable to record the full intensity of the shock.

In certain regions as Japan, the west coast of the United States, Panama, and, to some extent, Italy and New Zealand, the full strength of earthquakes except major ones is now measured. In California, for example, there are 50 instruments for this purpose located at 30 sites in 23 cities. In this case, in addition to observations on the ground, instruments are placed in upper stories of buildings. Special attention is also given to observing in regions of different geological conditions. Here, too, the observations are supplemented by determination of vibration-periods of buildings and other structures and of the ground itself--all important information to supplement and help to interpret that found at the time of an earthquake. A vibration-machine is used to give controlled vibrations of ground, buildings, and other structures. In a sense such observations give us complete earthquake-records for a great earthquake. It must be remembered, however, that the seismographs for the two purposes differ greatly in period and that the strong-motion instruments are started by the earthquake, and that there may be an interval between the time when other instruments stop because the recording goes off the sheet and the actual start of the strong-motion record. There is no way to be certain about this since as yet the strong-motion instruments have relative and not absolute time.

Records of interest during past year--In all eight different strong earthquakes have been recorded--one in Panama and the others in California. Only three of these are of special interest. These were: The submarine earthquake of July 6, 1934, recorded at Eureka, both by accelerograph and by displacement-meter--the first case of this sort; the Panama earthquake of July 18, 1934, recorded on an accelerograph at Balboa 100 miles from the epicenter--naturally arousing considerable interest at the Canal; and the records of the Lower California earthquakes of December 30 and 31, 1934, which were recorded at a considerable number of stations and especially the first large one at El Centro. This record was quite different from any other obtained probably on account of the great depth of sediments.

An interesting development was the perfection of a method of integration by which Mr. Neumann of the CGS was able to obtain a displacement-curve from the accelerograph-records. In the case of the earthquake recorded at Eureka (see above) he was able to derive a displacement-curve from the record of the so-called displacement-meter. The two gave quite good agreement. This is particularly important since there are many more accelerographs than displacement-meters and it thus becomes possible to determine the displacement. Periods of 15 seconds or even a minute are obtained in the displacement-curves thus worked out. The investigation of such periods is an interesting seismological problem.

There is so much interest in this program that by request of interested organizations monthly reports of progress are issued in mimeographed form.

Instrumental developments--Accelerographs have been perfected by widening the drums and improving the tape-devices, by the addition of base-line mirrors to give a line of reference for the various analyses to be made, and by the addition to a limited number of double magnification-systems so the strongest earthquakes can be recorded.

Vibration-meters have been developed and supplied with a wide range of magnification together with recorders which make it possible to observe simultaneously on several floors of a building.

A vibration-machine, called a micro-vibrator, has been developed for putting controlled vibrations into buildings or other structures on the ground.

Shaking-platform tests--Since earthquakes do not occur when we want them we would be much handicapped if we did not have shaking-tables. These have advanced far beyond the crude table which is capable only of simple harmonic motion.

During the past year noteworthy results have been obtained by the cooperation of the National Bureau of Standards and the CGS, notably Frank Wenner of the former and H. E. McComb of the latter, who have done most of the work outside of office hours. They have succeeded in testing all the principal teleseismic instruments of high magnification which can be placed on such a table. Credit should be given to Dr. Howard McClenahan of the Franklin Institute, Philadelphia (Pennsylvania), to Rev. Joseph Lynch, S.J., Fordham University (New York), and to Dr. Arthur L. Day, Geophysical Laboratory, CIW, for making possible tests of instruments which would otherwise not have been available. It is expected that it will be possible to define from these tests the limitation of reproduction of earth-movement possible with instruments based on the principle of the pendulum.

Small tables have been built for field-tests of strong-motion and vibration instruments, which should bring about improved results. These also make possible studies of limitation of such instruments in reproducing earth motion.

Crustal movements--These may be of several kinds: (A) Movements on a comparatively large scale which may or may not be accompanied by earthquake; (B) definite and visible slipping along a fault-plane, horizontal, vertical, or inclined, accompanying an earthquake; (C) block-tilting which is a form of (B) but with distinct characteristics; (D) localized changes which may or may not be accompanied by earthquake. There should probably be still another class to precede (A). This is continental movement such as that considered in the Wegener hypothesis. This will not receive consideration here.

In the case of (A), astronomical methods are hardly adequate. An excellent example of dealing with this problem is the triangulation executed for this purpose in California which is rigidly connected with the continental triangulation. The leveling may be considered in the same way. It may be pointed out that the stability of the western mountain-area must not be appraised too high in view of the movement over wide areas in certain earthquakes; for example, Pleasant Valley (Nevada) 1915, Cedar Mountain (Nevada) 1932, and north and Great Salt Lake (Utah) 1934.

In this connection, the following statement from Dr. William Bowie, Chief of Division of Geodesy, CGS, is of interest: "The aim in precise leveling to have a point within 25 miles of any point in the United States except inaccessible mountain-regions will be carried out by June 30, 1935. In precise triangulation, if the present rate is continued, 50-mile spacing will be complete within 12 months and 25-mile spacing within three years."

In the case of (B)--slipping along fault-plane--it is important to find out the extent of area affected. This was done successfully in 1906 even though the triangulation did not extend outside the area affected. It can be done much better in future earthquakes especially in California because of the careful spacing of triangulation-stations in regions most likely to be affected as worked out by the Advisory Committee in Seismology of the CIW and the CGS.

Examples of recent measurements of this sort include levels in the Imperial Valley and releveling after the Utah earthquake of March 12, 1934. Unfortunately, the releveling done after the earthquake of December 20, 1932, in Nevada had nothing previous in the region for comparison.

In the case of (C)--tilting of blocks--leveling is especially important. It has not yet been shown that it is important in the United States though fully established in Japan. Tiltmeter observations at Berkeley by cooperation of UC, CGS, and National Bureau of Standards are not expected to show block-tilting on a large scale but possible local tilt in the vicinity of the Hayward Fault. Since regular operation started there has been no tilt-action of the kind associated with earthquakes in Japan, but there has also been no earthquake along the Hayward Fault.

For (D) there has been local movement, such as sinking, over a considerable area in the region of San Jose (California) and ground-movements causing oil-pipes to be lifted into a bow above the ground, which were not accompanied by earthquakes, and we need to know more about the cause of such motions.

Problems--There are always more possible problems than can be carried out. A few pressing needs are suggested as follows:

(1) More stations equipped with vertical-component instruments. An example is the case of Harvard station with several hundred small earthquakes recorded only on the Benioff vertical. Another station with similar equipment suitably placed with regard to the Harvard station would have located many of these.
(2) Association of earthquakes and buried mountain structure.
(3) Better determination of position and determination of depth of central United States earthquakes through additional stations.
(4) Wider studies of tilt.
(5) Quantitative studies of seismic sea-waves.
(6) Geophysical investigation of seismological station-sites to study influence of local structure on the seismological record.
(7) Use of geophysical methods to locate faults.
(8) More employment for competent seismologists.

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[2] Destructive and near-destructive earthquakes in California and western Nevada--1769-1933, U.S. Coast Geod. Surv., Spec. Pub. 191, 1934.
[3] A new map of earthquake-distribution, Geog. Rev., v. 25, pp. 125-130, 1935.
[4] List of seismic sea-waves, Annales de la Commission pour l'Etude des Raz de Marée, No. 4.
[5] The California strong-motion program of the United States Coast and Geodetic Survey, Bull. Seis. Soc. Amer., v. 25, pp. 81-95, 1935.

U. S. Coast and Geodetic Survey,
Washington, D. C.

A STUDY OF SOME SEISMOMETERS

G. A. Irland

(Abstract)

This paper discusses the advantages of seismometers that record displacement over instruments that measure velocity or acceleration. It shows that a portable seismometer using changes in

capacitance between condenser-plates to produce proportionate changes of current in an oscillograph has many good characteristics, chief of which are the ease and accuracy with which calibration may be made in the field after sensitivity has been adjusted as desired.

Several types of vertical-component instruments were built and tested on the mechanical oscillator. These are described and their characteristics discussed. Oscillograph-records for transient as well as steady-state vibrations having frequencies of 2 to 70 cycles per second show curves of actual motion on the same record with those registered by the seismometer. Peculiarities at critical frequencies can thus be discovered and corrected. Finally, a vertical-component seismometer in which the change in pull of the supporting spring is compensated by change in radius-arm at which the spring-force acts was developed during the investigation. Performance of this instrument is shown to be excellent for a frequency range of 2.5 to 22 cycles per second. As earth-vibrations due to blasting usually have a frequency of 10 to 15 cycles per second, this instrument is well suited for investigating disturbances of this type. A horizontal-component seismometer having approximately the same design constants as the vertical-component instrument was also developed and is described.

The appendix gives a mathematical analysis of the motion of the center of oscillation of the seismometer arm and offers examples of computations by which performance of an instrument may be determined theoretically.

The importance of fidelity in recording transient effects is discussed; seismometers should be so designed that the initial value of the transient effect is negligible. Tests on the mechanical oscillator show good agreement between curves of actual motion and seismometer-records for complicated transients.

Direct spring-support for the arm of a vertical-component seismometer is shown to be unsatisfactory. The theory of geometrical compensation is developed, and computations are made showing application of the theory to actual design.

[The complete paper is published as Technical Paper 556 (48 pages) of the United States Bureau of Mines, and copies may be obtained from the United States Printing Office, Washington, D. C., at 10 cents each.]

Bucknell University,
Lewisburg, Pennsylvania

THE PROPAGATION OF RAYLEIGH WAVES IN HETEROGENEOUS MEDIA

Chaim L. Pekeris

(Abstract)

A method is given for obtaining a power-series expansion in the wave-length for the Rayleigh wave-velocity in a half-space whose density ρ and elastic constants λ and μ are functions of depth. This is followed by a discussion of the Rayleigh wave-problem in media 1, 2, and 3, in which $\lambda = \mu$, and $(\rho/\rho_0) = (\lambda/\lambda_0) = \cos^2 \beta z$, $e^{2\beta z}$, $(1+\beta z)^2$, respectively. Starting with the value of $0.9194\sqrt{\mu/\rho_0}$ for zero wave-length, the wave-velocity in medium 1 increases indefinitely with increasing wave-length and heterogeneity, while the wave-velocity in medium 2 approaches the finite limit of $\sqrt{8\mu/3\rho_0}$. The group-velocity in medium 1 goes through a minimum, then a maximum, from where it continuously diminishes with increasing wave-length. The group-velocity in medium 2 goes through a minimum and then rises asymptotically to the limiting value of the wave-velocity. In medium 3 both the wave-velocity and the group-velocity rise to the value $\sqrt{\mu/\rho_0}$ at the critical wave-length. In all three media the wave-velocity is everywhere greater than the group-velocity. The ratio of the vertical to horizontal amplitudes at the surface decreases in all three media with increasing wave-length.

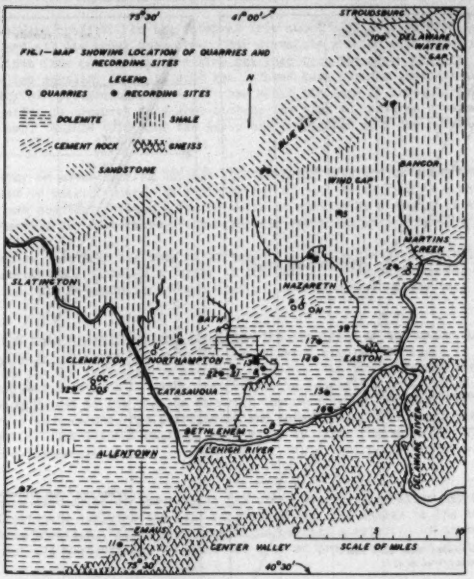
[The complete paper is published in Physics, v. 6, pp. 133-138 (1935).]

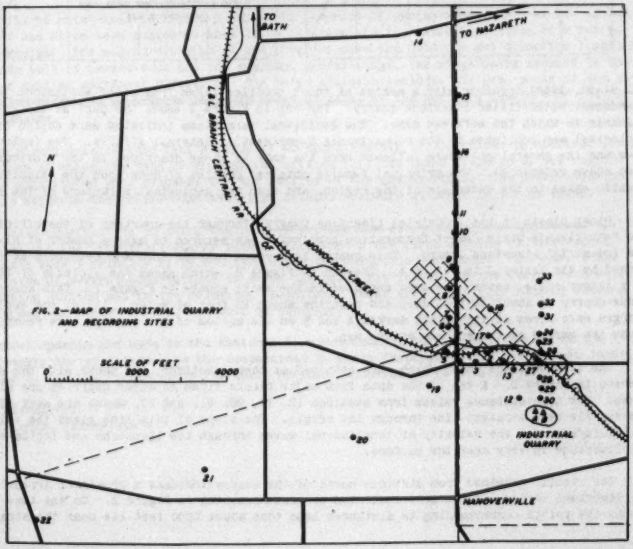
Massachusetts Institute of Technology,
Cambridge, Massachusetts

PROPAGATION OF ELASTIC WAVES IN LIMESTONE

Maurice Ewing and A. P. Crary

This report covers a continuation of the seismological investigations of quarry-blasting reported a year ago (Ewing, Crary, and Lohse, Trans. Amer. Geophys. Union, 15th annual meeting,


75°30'
40°00'
STROUDSBURG
DELAWARE WATER GAP
FIG. 1—MAP SHOWING LOCATION OF QUARRIES AND RECORDING SITES
LEGEND
QUARRIES
RECORDING SITES
DOLOMITE
SHALE
CEMENT ROCK
GNEISS
SANDSTONE
N
BLUE MTS.
WIND GAP
BANGOR
MARTINS CREEK
SLATINGTON
NAZARETH
BATH
CLEMENTON
NORTHAMPTON
EASTON
CATASAUQUA
BETHLEHEM
ALLENTOWN
LEHIGH RIVER
DELAWARE RIVER
EMAUS
CENTER VALLEY
SCALE OF MILES
40°30'
75°30'


TO BATH
TO NAZARETH
LEHIGH BRANCH CENTRAL R.R.
MONOCACY CREEK
FIG. 2—MAP OF INDUSTRIAL QUARRY AND RECORDING SITES
SCALE OF FEET
0
2000
4000
N
INDUSTRIAL QUARRY
HANOVERVILLE

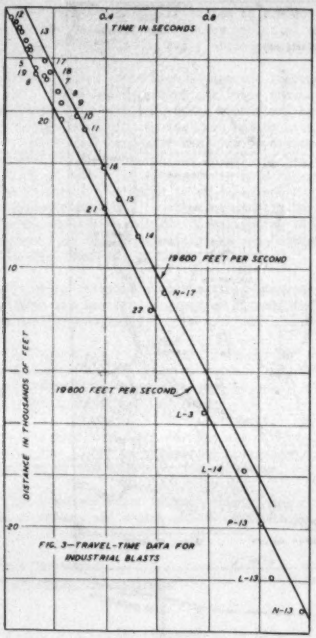


FIG. 3—TRAVEL-TIME DATA FOR INDUSTRIAL BLASTS

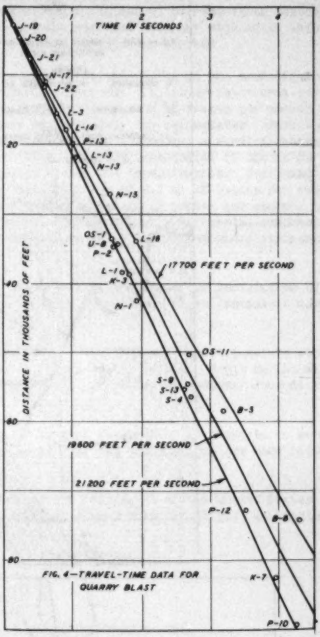


FIG. 4—TRAVEL-TIME DATA FOR QUARRY BLAST

pp. 91-94, 1934) together with a series of short profiles taken from minor explosions in an abandoned, water-filled limestone-quarry. The map in Figure 1 shows the part of eastern Pennsylvania in which the work was done. The geological formations indicated were copied from the geological map published by the Pennsylvania Department of Internal Affairs. The instruments used and the general procedure followed were the same as those described in the previous paper (see above reference). The principal results obtained consist of data upon the velocity of elastic waves in the materials of the region, and upon the geological structure of the region.

Minor blasts in the Industrial Limestone Quarry--Through the courtesy of the officials of the Pennsylvania-Dixie Cement Corporation permission was secured to make a number of blasts in the Industrial Limestone Quarry. This quarry is located between Bath and Bethlehem at the point marked by the letter J in Figure 1. The map in Figure 2, which shows the vicinity of the quarry on a larger scale, covers the area enclosed in the small square in Figure 1. This abandoned limestone-quarry is about 50 feet deep and contains about 15 feet of water. All of the explosive charges were fired at the points marked A and B on the bottom of the quarry. The recording stations are marked by the numbers on the map.

The time-distance data, which were obtained at these stations, are shown with the station numbers in Figure 3. A few of the data from major blasts fired in other quarries are also shown. The time-distance values from stations 12, 19, 20, 21, and 22, which are west of the quarry, lie on a straight line through the origin. The slope of this line gives the value, 19,600 ft/sec, for the velocity of longitudinal waves through the limestone and indicates that the limestone is very near the surface.

The results obtained from stations north of the quarry indicate a prominent irregularity in the limestone throughout the zone indicated by cross-hatching in Figure 2. On the time-distance graph, the points corresponding to distances less than about 2000 feet lie near the straight line

obtained from the westward profile. In the interval from about 2000 feet to 4000 feet the points are badly scattered and all lie above this line. For distances greater than about 4000 feet the points lie on a straight line parallel to the line obtained from the other profile. The time-interval between the two parallel lines is 0.08 sec. These data clearly indicate that the waves travel with a velocity of approximately 19,600 ft/sec until the zone of irregularity is encountered. The time required to traverse this zone exceeds the time to traverse a normal zone of equal width by 0.08 sec. Beyond this zone the waves are propagated with the normal speed for limestone.

The loss of energy in waves passing through the irregular zone was so great that large charges had to be used to obtain records at stations beyond it. At station 14 a charge of 25 pounds of explosive was needed to obtain a record while at station 22 a charge of 4 pounds was sufficient. Approximately the same ratio of charges held for all stations along these two lines.

It will be noted at once that the zone of irregularity in the limestone coincides with the valley of the Monocacy Creek. Although a survey of the wells in this zone has not yet been made it is known that in one of the wells occasional beds of sand were encountered to a depth of 75 feet.

Major blasts from cement and limestone quarries--The locations of the major quarry-blasts which have been studied to date are indicated by the lettered circles in Figure 1. The positions of the recording stations are indicated by numbered crosses. The time-distance data which have been obtained are plotted in Figure 4. Each observation is identified by a letter and a number, which refer to the quarry and to the station at which the record was obtained. Although many later phases appear on each record, the correlation and identification of these phases have not been entirely completed. The present analysis is limited to first phases only. Also included in Figure 4 are data from the westward profile from the Industrial Quarry as described in the preceding section.

To facilitate the discussion of the results the area under consideration may be divided into three parts. The first part includes the belt of cement-rock, the shales to the north of it, and the sandstones of Blue Mountain. It is seen from Figure 4 that a velocity of approximately 23,200 ft/sec is obtained for all observations in which the path of propagation lies entirely in these formations.

It will be noted that in Figure 1 two small outcrops of gneiss occur north of the Lehigh River. It has often been suggested that these outcrops are the exposed portions of a buried ridge of gneiss. The second division of the area includes the dolomite and dolomitic limestone between the belt of cement-rock and the supposed gneiss-ridge, the ridge being assumed to continue in a west or southwest direction. The third division includes the area south of the assumed gneiss-ridge. A pronounced fault is known to exist at the northern boundary of the outcrops of gneiss.

From Figure 4 it is seen that a velocity of approximately 17,700 ft/sec is obtained for all observations in which the path of propagation extends into the third division of the region. This fact constitutes good evidence for the reality of the gneiss-ridge. The observation at station 11 supports the belief that the ridge extends westward at least as far as Emaus.

The only observations in which the path of propagation lies entirely in the second division of the area are the Industrial Quarry blasts described in the first section of this report. These blasts gave a velocity of 19,600 ft/sec for the dolomitic limestone. In Figure 4 are shown results of several observations in which the blast was located in the cement-rock while the recording station was in the dolomitic limestone. These give velocities ranging between 19,600 ft/sec and 21,200 ft/sec, as would be expected.

Acknowledgments are made to the National Research Council for a grant-in-aid, to the Trojan Powder Company for explosives, to the Geophysical Research Corporation for the seismic instruments, and to the quarry operators for their splendid cooperation in this project.

Lehigh University,
Bethlehem, Pennsylvania

THE MOTION OF A VISCOUS FLUID UNDER A SURFACE-LOAD WITH PARTICULAR REFERENCE TO THE PLEISTOCENE ICE-SHEETS

N. A. Haskell

(Abstract)

The problem of the motion of a semi-infinite, incompressible, viscous fluid under a radially symmetrical pressure applied on the free surface yields a simple formal solution when it is assumed that the viscosity is so high that the acceleration-term in the equations of motion can be neglected in comparison with those arising from viscous forces, and when the displacement of the surface is small relatively to the radial dimensions of the load. The general solution is valid, subject to these restrictions, for any symmetrical load, σ, and for arbitrary initial motion of the fluid. The particular case where $\sigma = 0$ and the fluid returns to equilibrium from an initial displacement may be applied to the plastic recovery of the Earth after the disappearance of the Pleistocene ice-sheets. F. Nansen's curves giving the post-glacial uplift as a function of the time at a point near the center of the Fennoscandian glaciated region and at Oslo may then be used in connection with the theory to determine the mean viscosity of the outer shells of the Earth. The kinematic viscosity, ν, is found to be of the order of 3×10^{21} c.g.s. units ($cm^2\ sec^{-1}$).

[The complete paper is to be published in Physics.]

Massachusetts Institute of Technology,
Cambridge, Massachusetts

CHARACTERISTICS OF DEEP-FOCUS EARTHQUAKES

G. J. Brunner

A fracture in the crystalline layer of the Earth's crust extending to a depth of about 40 km gives rise to what is termed a normal or surface earthquake. These comprise the majority of seismic disturbances.

They were long considered the only ones possible, yet evidence has forced us to extend our views. A focus below the crystalline layer, that is, deeper than about 40 km, gives rise to a deep earthquake. How rapid vibrations can originate in the glassy material of high temperature is a complete mystery to us.

The percentage of deep quakes of the total number of seismic disturbances is not known even approximately, still it appears to be large. Perhaps one-fourth of all the world-quakes have a deep-focus origin. The monthly bulletins of the St. Louis earthquake-station for 1934 list 138 earthquakes for that year out of which 33 or nearly one-fourth are described as deep-focus quakes. Sometimes for a period of several months more than 50 per cent of the disturbances are deep-seated. Of course no claim is made to complete accuracy in our present state of knowledge, that is, some quakes may erroneously have been marked as deep whilst others may have been overlooked, so that the ratio of one-fourth remains about the same.

The depths at which seismic disturbances can occur are astonishingly great. The writer has recently completed an analysis of the quake of June 29, 1934, and found a depth of 700 km. This depth is 11 per cent of the Earth's radius or 437 miles--a distance from Washington to Ottawa.

Further, we may recognize the law of diminishing frequency with increasing depth, that is, more quakes occur at a depth of 100 km than at 200 km, etc. Quakes at a depth of 500 to 700 km seem to occur only several times a year.

We find distributed over the Earth zones of predominant depths. On the North American Pacific Coast we find generally depths of 100 km; in Peru, Bolivia, and Chile, almost every disturbance strong enough to be recorded at great distances is from 100 to 200 km deep; the region about Japan abounds in foci of 300-km depth, while a great arc around the north of Australia is disturbed to the greatest depth of from 400 to 700 km. In general, every zone of known seismic activity is also the seat of deep disturbances.

As is obvious, the depth of focus profoundly affects the travel-times of all earthquake-waves, so that for the analysis of deep quakes, that is, for the determination of the epicenter, time of occurrence, and depth, our ordinary tables become increasingly inadequate with increasing depth and distance.

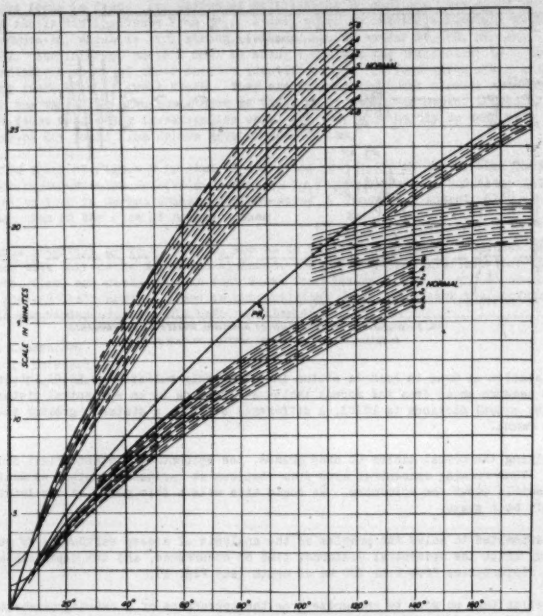


FIG. 1—DEPTH-TIME VERSUS DISTANCE OF DEEP EARTHQUAKES

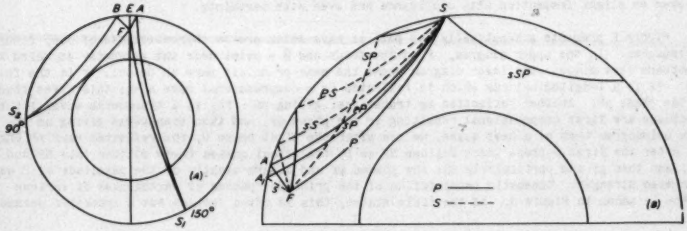


FIG. 2—PATHS OF RAYS [AFTER STECHSCHULTE (a), AFTER K. J. SCRASE (a)]

In practice we can with ordinary or surface tables still obtain a tolerably good solution when the depth does not exceed 100 km and the distance is small. Thus when a quake occurred on the Mexican Coast in the Pacific of about 100-km depth, as they frequently take place, the American stations will be able to obtain a tolerable solution by the ordinary tables, that is, the (S-P) intervals yield a fair approximation to the true epicentral distance, and time of occurrence. But beyond 30° and 40° the error increases rapidly. A Chilean earthquake, for instance, has an epicentral distance of about 60° from the American stations. If we assume a depth of 200 km and an (S-P) interval of 8 minutes at a particular station and treating it erroneously as of normal depth, the epicentral distance is found to be 57°1. The true distance is 60°2, a difference of more than 3° or over 200 miles.

We further take the extreme case of the earthquake of June 29, 1934, whose focal depth is

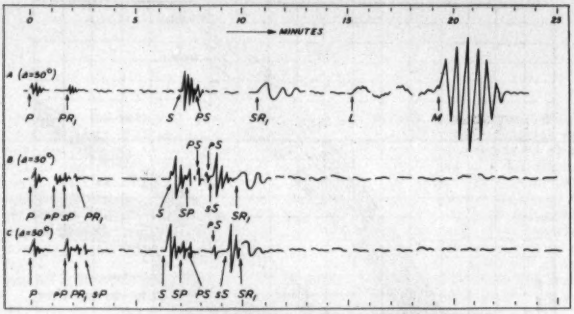


FIG. 3—SCHEMATIC PRESENTATION OF PRINCIPAL PHASES OF EARTHQUAKES
A=NORMAL DEPTH, B=300-KM DEPTH, C=500-KM DEPTH

700 km. The station at Graz in Austria states in its monthly bulletin an (S-P) interval of 11 minutes and 4 seconds which from the normal tables corresponds to an epicentral distance of 91°5 whilst the actual distance is 107°3, a difference of 15°8, a distance greater than from Washington to Omaha.

When applying the normal tables to deep quakes, the epicentral distances fall short in various amounts. Thus drawing epicentral arcs from stations at various azimuths, we would obtain circles, concentric about the epicenter. We could thus make a fair guess at its location, but this would only be a guess.

We have attempted to solve the problem of the analysis of a deep earthquake by means of a depth-chart, by which the epicentral distance, time of occurrence, and the depth can be rapidly found for all disturbances from 0 to 700 km of depth (see Fig. 1).

It is obvious that we wish to recognize from the appearance of a seismogram whether an earthquake had a focus of normal or abnormal depth. We have several criteria enabling us to do so even on slight inspection with confidence and even with certainty.

Figure 2 presents schematically the path of rays which are so characteristic of deep-focus earthquakes. In the upper diagram, F is the focus and B a point near the epicenter at which reflections take place. The lower diagram shows the same principle more in detail. F is the focus. FA is a longitudinal ray which is reflected as a compressional wave also; this gives rise to the phase pP. Another reflection is transverse, giving pS. FA_1 is a transverse wave; its reflections are first compressional resulting in the phase sP, and then transverse giving us sS. On a seismogram then of a deep quake, we see after the first phase P, the reflected rays pP and sP; after the first S-phase there follows SP as in the normal quakes (here divided into SP and PS); and then pS and particularly sS; the phases pP and sS are usually of the magnitude of P and S or even stronger. Schematic presentation of the principal phases of earthquakes of various depths is shown in Figure 3. As the title states, this is not a factual but a synthetic seismogram.

The upper line gives the usual principal phases of a normal earthquake at 50° epicentral distance. The phases P, PR_1, S, SR_1, L, and M are placed at the correct intervals. When the depth of focus is normal, that is, about 15 km or in general within the crystalline layer, the surface-waves are most pronounced. Their amplitudes are usually from 10 to 30 times that of the S-phase. The characteristics of a surface-quake are the following: Practically only the few phases P, PR_1, S, and SR_1, and enormous surface-waves. Of course at other distances other phases will appear, such as PR_2, or SKS--yet after all the phases are few.

The second line of Figure 3 reproduces a seismogram of an earthquake of 300-km depth also at 50° distance. The first phase after the P is pP--the characteristic reflection from a deep focus; it is a phase usually quite as strong as P, or stronger. The following PR_1 and sP are generally weaker. The S-phase is earlier than that from a normal depth; this phase is sometimes enormous as compared with P. The sS-phase is quite large; in fact the conspicuousness of sS is a criterion of depth of focus. When this outstanding phase is absent, the depth is normal; when strongly

developed, the focus is deep. Its period of oscillations is much the same as of the S-phase and is therefore easily distinguished from SR_1. A deep quake is therefore strongly evidenced by this train of S-phases--S, which is very strong, followed by the weaker SP, PS, pS, and finally by the strong sS. The interval sS to S must be about 1.8 times the interval pP to P from Poisson's law, and furnishes a check of their correct identification. Surface-waves are practically absent--an easy indication of great depth. They are frequently absent already when the depth is only 100 km, but may still have amplitudes as large as S; at 200-km depth, traces of surface-waves may be found on careful investigation only; but they will hardly be seen at a first glance. No surface-waves are found from depths greater than 300 km.

The third graph of Figure 3 is that of an earthquake of 500-km depth, also at 50° distance. No new phases appear but the intervals differ; pP to P becomes larger, and also sS to S; PR_1 and SR_1 come earlier than in normal quakes; surface-waves of course are absent. The (S-P) interval becomes smaller than in the case of normal quakes.

The three intervals pP to P, S to P, and sS to S are interdependent, increasing according to fixed laws with increasing depth and distance, and are therefore available for the determination of depth, time, and distance. In fact these four phases P, pP, S, and sS are our principal means. By stating their arrival times in our bulletins we will increase the usefulness of these publications and render considerable help to other investigators.

Geophysical Laboratory,
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St. Louis, Missouri

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AMERICAN GEOPHYSICAL UNION

Sixteenth Annual Meeting

SECTION OF METEOROLOGY

Washington, D. C.
April 25, 1935

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CLOUD-OBSERVATIONS IN SHORT-TERM FORECASTING OF SNOW-STORMS

Charles F. Brooks and E. Monroe Harwood, Jr.

This paper presents another example of the usefulness of clouds as an aerological aid in forecasting [cf. reference 1].

Blue Hill Observatory is expected to be Harvard University's watch-dog for snow-storms, ice-storms, and cold waves. The highly Harvard towns of Brookline and Milton also ask for similar service; Ernest B. Dane, of Brookline, generously provided funds for a study of forecasting winter snow-storms. Though the principles of forecasting snow from synoptic charts are well known, cloud-observations have been found of decided help in adding details and, not infrequently, in conjunction with temperature, pressure, and winds on Blue Hill and on Mt. Washington, in telling on a synoptic forecast of "rain or snow" whether it will be "rain" or "snow," a difference of great practical importance.

We try to predict a few hours in advance the time when snow will begin, how soon it will reach plowing depth, the rate at which it will continue, how much will accumulate--which will sometimes differ appreciably in an altitude difference of 100 to 200 feet--whether or not it will drift, when snow will stop, and what melting, if any, is in prospect, or, if the snow is wet, when it will freeze. Obviously, cloud-observations cannot tell all these but are of value for the time of beginning, the general intensity and duration, and for the near approach to the end. A summary of past experience at a station is a helpful guide to what may be expected under more or less similar circumstances in the future.

Since the cirrus clouds give the first local prognostic of the approach of a storm, any tabular guide to past snow-storms for forecasting purposes must begin with certain categories of these cirrus clouds. Form might be used [2], but perhaps the most important information to be derived from the cirrus is the general temperature-gradient in the atmosphere. The pressure-gradients aloft slope fairly in accordance with the general temperature-gradient. Therefore, both direction and velocity of the cirrus yield important information regarding general temperature-distribution about the observing station. The direction of motion will be about 90° to the right of the gradient and the velocity will be proportional to the gradient [3]. The direction of motion of the cirrus has been used as the first criterion for our tabulation. Velocity comes second. Not having the actual height of the cloud in most cases, it becomes necessary to reduce the angular velocity to what the actual velocity would be if the cirrus were at the mean winter height of 8884 meters found by Clayton for Blue Hill [4]. This is not the true velocity but an approximation to it, which affects all observations equally.

With no more cases than can be put onto a sheet or two, the reference-table is in readily useful form if the cases are arranged simply in accordance with the direction of cirrus motion. Other tables could be made giving velocity of cirrus or, indeed, any other preliminary, the first place. In a long line for each storm are placed numerous categories of information: Direction, velocity, kind, and amount of the cirrus; date and time of observation; higher intermediate clouds, if any, direction of motion from south or north relative to that of cirrus, actual direction and velocity; same for lower intermediate clouds with respect to upper; pressure-tendency and rate at time of observation; temperature at 12-hour intervals from cirrus appearance till snow; tendencies in pressure and temperature at Mt. Washington, also wind-direction and wind-velocity last observation; sequence of snow-characteristics; precipitation total within 24 hours of appearance of cirrus, total for storm, snow-depth, times of beginning and ending of snow-fall, duration, and interval between first cirrus and beginning of snow. Such a table makes possible ready reference to past snow-storm data and shows in connection with the first observation of cirrus in an approaching storm what ensued on other occasions when cirrus came from the same direction. Furthermore, weather-maps can be consulted and points of similarity or dissimilarity of past maps preceding heavy snows noted in comparison with the current map.

For an initial study we here attempt to state statistically what the motions of upper and intermediate clouds before a heavy snow-storm at Blue Hill are, and impressionistically some immediate snow-indications of intermediate and lower clouds. The storms were grouped into two categories, namely, those yielding 11 inches or more and (2) those between 6 and 11 inches. Harwood tabulated these and prepared the summarizing diagrams. The 33 years, 1890 to 1920 and 1932 to 1934, were covered.

Figure 1 shows that the first cirrus before a snow-storm of consequence comes either from between west by north and northwest or between west by south and south-southwest, and that there is nearly the same number in the northern and southern category of each group of storms. Furthermore, there is no apparent difference between the very heavy and the heavy snow-groups. For

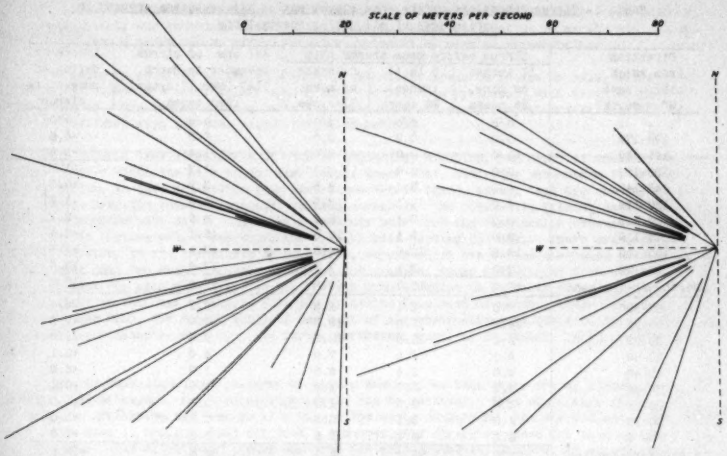

FIG. 1—DIRECTION AND VELOCITY OF CIRRUS MOVEMENT BEFORE 6- TO 10-INCH SNOW-STORMS (LEFT) AND 11- TO 18-INCH SNOW-STORMS (RIGHT) AT BLUE HILL OBSERVATORY

both together, 16 out of the 25 northwesterly motions were between 12° and 38° north of west, averaging about west-northwest, and 23 of the 32 southwesterly motions were between 11° and 42° south of west, averaging about west-southwest. No snow-storm of 6 or more inches followed cirrus moving from more than 51° north of west.

In comparing these with all cirrus motions observed from 1887 to 1889 and tabulated by Clayton [5] into 10°-groups, we find that there is no minimum of cirrus motions from the west, as in the case of snow-storm cirrus, and that there are plenty of cases of cirrus moving from north of northwest and from easterly quarters. Table 1 gives the details. It is evident that cirrus motions from 40° to 79° and from 100° to 109° are distinctly snow-storm prognostics, since they exceed the normal frequencies for these directions by from 43 to 363 per cent and an average of 72 per cent.

Rapid cirrus movements, exceeding the winter-time average, 38.1 meters/sec [6], occurred before 14 of the 25 big snow-storms and before 24 of the 32 lesser ones. This larger proportion for the lesser storms is to be expected, since fast air-currents usually go with fast-moving storms, which would not yield such a quantity of snow in their brief stay as the slow-moving ones would. Table 2 shows the speed of the cirrus by quadrants for the two categories of storms.

There is no apparent relation between cirrus direction and the interval before the snow began (see Table 3). Before the biggest snow-storms cirrus from the northwest-quadrant were observed at a median of 19 hours (maximum 64, minimum 8) before the snow began, and from the southwest-quadrant, 22 hours (maximum 30, minimum 6). Before the smaller snow-storms the median interval between cirrus from the northwest-quadrant and the beginning of precipitation was 17 hours (maximum 43, minimum 7), from the southwest-quadrant the median interval was 23 hours (maximum 72, minimum 9). The median for all cirrus is 24 hours [7]. From this it appears that the storms preceded by cirrus from the southwest move more slowly than those from the northwest, and that cirrus before heavy snow-storms are followed by snow at a median-interval four hours less than that for any precipitation following the appearance of cirrus. Furthermore, while 38 per cent of all cirrus observations are followed by precipitation within 24 hours [7], 65 per cent of the cirrus before heavy snow-storms were followed by precipitation within 24 hours.

The duration of the precipitation, sometimes intermittent and including rain which fell before, after, or in the middle of the storm, varied greatly (see Table 4). The median for the big storms is found to be 30 hours, with 28 after northwest-motions and 32 after southwest-motions, and for the lesser storms 26 hours, with 32 for the northwest and 23 for the southwest

Table 1--Cirrus directions before snow-storms and on all occasions grouped in percentages of all cirrus observations

Direction from which cirrus came (0° = south)	Cirrus before snow-storms with 11 inches or more, 25 cases	6 to 11 inches, 32 cases	6 inches or more, 57 cases	All obs. of cirrus November to March, 1887-1888 (Clayton) 1096 cases	Excess or defic. of snow-storm cirrus
° °	o/o	o/o	o/o	o/o	o/o
170-179	0.0	0.0	0.0	0.6	-0.6
160-169	0.0	0.0	0.0	1.4	-1.4
150-159	0.0	0.0	0.0	1.7	-1.7
140-149	4.0	3.1	3.5	3.2	+0.3
130-139	4.0	3.1	3.5	4.9	-1.4
120-129	0.0	9.4	5.3	8.0	-2.7
110-119	12.0	9.4	10.5	10.1	+0.4
100-109	16.0	12.5	14.0	10.1	+3.9
90- 99	12.0	3.1	7.0	17.6	-10.6
Northwest-quadrant	48.0	40.7	43.8	57.6	-13.8
80-89	0.0	3.1	1.8	8.2	-6.4
70-79	24.0	15.6	19.3	10.7	+7.6
60-69	8.0	15.6	12.3	7.5	+4.8
50-59	8.0	6.2	7.0	4.9	+2.1
40-49	4.0	9.4	8.8	1.9	+6.9
30-39	0.0	3.1	1.8	1.9	-0.1
20-29	4.0	0.0	1.8	0.8	+1.0
10-19	4.0	3.1	3.5	0.5	+3.0
0- 9	0.0	3.1	1.8	0.2	+1.6
Southwest-quadrant	52.0	59.2	56.1	36.6	+19.5
Southeast-quadrant	0.0	0.0	0.0	2.9	-2.9
Northeast-quadrant	0.0	0.0	0.0	3.0	-3.0

Table 2--Cirrus speeds in meters per second by quadrants before heavy snow-storms

Quadrant from which cirrus came	Median velocity		Maximum velocity		Minimum velocity	
	11 inches or more snow	6 to 11 inches snow	11 inches or more snow	6 to 11 inches snow	11 inches or more snow	6 to 11 inches snow
Northwest	49	45	73	62	17	19
Southwest	51	47	74	75	6	24
All	51	46	74	75	6	19

Table 3--Interval in hours between cirrus and beginning of precipitation

Quadrant from which cirrus came	Median interval		Maximum interval		Minimum interval	
	11 inches or more snow	6 to 11 inches snow	11 inches or more snow	6 to 11 inches snow	11 inches or more snow	6 to 11 inches snow
Northwest	19	17	64	43	8	7
Southwest	22	23	30	72	6	9
All	20	20	64	72	6	7

Table 4--Duration in hours of precipitation according to direction of motion of preceding cirrus

Quadrant from which cirrus came	Median duration		Maximum duration		Minimum duration	
	11 inches or more snow	6 to 11 inches snow	11 inches or more snow	6 to 11 inches snow	11 inches or more snow	6 to 11 inches snow
Northwest	28	32	119	70	21	6
Southwest	32	23	74	109	19	8
All	30	26	119	109	19	6

A few of the storms stretched out into days, especially some of the big ones, whose large totals in such cases were due to their long continuation. Although there are differences between the northwest- and southwest-groups for each class of storms, they are in opposite directions and of

insufficient size, in view of the limited number of cases, to indicate any rule. The shortest of the big storms was 19 hours, after cirrus from the south-southwest at 38 meters/sec, and of the lesser ones 6 hours, after cirrus from the northwest by west at 49 meters/sec.

The depth in relation to the direction of the cirrus seems to follow no rule, either. The biggest six storms are about evenly spaced from southwest to northwest, with three of them in each quadrant. The two 10-inch falls in the lower snowfall-group come at practically the extreme directions, with the nine storms sprinkled between.

This general lack of relation of time of beginning, duration, and depth of snowfall to the direction from which the high clouds came simply means that, since the snow-storm is part of a moving system, it does not matter from what direction it comes, except that the snowing portion must remain over the point of observation long enough for the constantly falling snow to accumulate to a considerable depth. Such heavy snow may come from any combination between a large rate of fall lasting only a few hours and a small rate lasting for days. There are definite limits, however, in the experience at Blue Hill, beyond which the cirrus movements go with storms that either have too small a supply of vapor--for example, those with cirrus from north of northwest--or have too much warm maritime air for the precipitation to be heavy snow, which is probably the limit in the case of storms heralded by cirrus from east of south. These limits are more apparent than real, for rarely (only 10 per cent of all observations of Table 1) do cirrus clouds under any circumstances come from the north, northeast, east, or southeast, in the colder half-year.

Some big snow-storms are preceded by cloudy weather, so that there are no cirrus clouds in advance. Nevertheless, the wind at high levels can be surmised. That of January 23-24, 1935, is an example. Following the passage of a strong low early January 22, the sky did not clear, owing to a large flow of tropical Gulf air from a southwesterly direction above the cold northwesterly surface-wind. The altostratus opacus was from the west-southwest, at about 33 meters/sec, but the general body was probably moving from the southwest, because there was a light sector marking the thinning of the cloud to the northwest. These clouds continued all day, in the late afternoon being thinnest to the west-northwest, while the wind at the surface swung toward north. Reflections of city lights in the evening showed the cloud-base to be at about 2000 meters in the north and at about 1500 meters in the southeast. The base of the altostratus opacus was from west, about 16 meters/sec early on the morning of January 23, and the sky was still light to the northwest, indicating movement of the main mass of cloud from the southwest.

In fact, Mt. Washington, while in the west wind, 18 meters/sec at 2000 meters, observed higher clouds from the south. In view of the more expanded condition of the air over the sea than over the cold land and, therefore, favoring higher pressures at moderate elevations, it seems probable that the wind aloft went round through the south from the west observed at the altostratus and altocumulus level, to the east-southeast at the stratocumulus level. The wind-structure at 8 a.m. January 23, 1935, then was approximately as follows: At 6000 meters south; at 4000 meters southwest; at 2000 meters west (18 meters/sec); at 1500 meters (south); at 1000 meters east-southeast (13 meters/sec); and at 200 meters northeast (7 meters/sec). Such conditions favored (1) a general ascent of maritime air over cold air over the land and (2) an overturning of the lower atmosphere owing to the instability caused by the warm damp-current from the southeast under the colder west-wind aloft. On this occasion, heavy snowfall for at least 12 hours was forecast; snow began at 9 a.m. and continued for 25 hours.

The next morning, at the end of the storm after 16 inches of snowfall, with 2.40 inches of water-content, the highest clouds, altocumulus praecipitans, were moving from the southwest by south at about 13 meters/sec, while the wind at the top of Blue Hill was from the northwest at 13 meters/sec. The directions at intermediate levels were probably between these, for the cessation of snowfall indicated that atmospheric stability was increasing.

The time of beginning of snowfall may be told fairly accurately up to an hour or two in advance when altocumulus or altostratus clouds are visible. The altostratus is, by definition, a dense cloud of (falling) snow, so the rate of descent of its under-surface can be used to time the arrival of snow at the ground, providing that allowance is made for evaporation if the lower air is dry. The altocumulus is a lumpy cloud, the details of which disappear when snow falls through it. With snow falling at about one meter/sec and the altocumulus immediately before snowfall at 2000 to 3000 meters, there is, obviously, at least half to three-quarters of an hour warning from the disappearance of the detail. Low, secondary fractocumulus may form from the chilling action of the snow, thereby giving perhaps 20 minutes' warning, while their disappearance in turn behind the snow-screen shows the immediate prospect of snow in 10 or 15 minutes.

When it is already snowing, a lightening of the clouds is a prognostic of an early ending

of the snow, either by changing to rain or by cessation of precipitation. If there are alternations of dull and light in the course of a few minutes during a snow-storm, it is evident that the cloud-sheets are breaking and that snow will no longer fall heavily and is likely to stop within a few hours at most. A pink glow at sunset while snow is falling is a prognostic of the early cessation of snowfall unless the snow has continued for a long time (indicating slow motion of the storm) or unless the storm is moving from the south.

These several indications from clouds are valuable supplements to the information from weather-maps, from local observations, from upper-air data, from Mt. Washington, and, to add a modern touch, from the lapse-rates indicated by the transmission of ultra-high-frequency radio waves over long paths [cf. 8]. They make short-term warnings of heavy snow for highway and railroad interests more valuable.

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ANALYTICAL APPROACH TO THE METHODS OF PHYSICAL WEATHER-ANALYSIS

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The trend of meteorology in recent years has been marked by an effort to make more and more use of physical methods in everyday practice. It is therefore fitting to scrutinize the foundations upon which we may construct a system of physical weather-analysis and to attempt to indicate some of the leads which may be followed in developing such a system. Before we may do this, it is necessary to consider the nature of physical weather-analysis.

Physical weather-analysis (L. P. Harrison, Mon. Weath. Rev., v. 62, pp. 157-159, 1934) has been defined as a physical analysis of the state of the atmosphere and the activities going on within it. This consists of two parts:

(a) Air-mass analysis--Identification and delimitation of air-masses, that is, analysis of the magnitudes and distribution of characteristic properties and other significant meteorological elements of the air-masses; classification of the air-masses according to source-region and principal modifications due to trajectory over land- and water-surfaces; and determination of the position, structure, nature, etc., of the various fronts and surfaces of discontinuity (zones and layers of transition) or boundaries of the air-masses.

(b) Dynamical weather-analysis--Analysis or diagnosis of the physical activities underlying given weather-conditions, that is, a study of present and past weather-situations to describe the nature of the activities, such as precipitation, cloudiness, definite relative motions of adjacent air-masses, etc., which are occurring in the given weather-situation and to determine the physical causes which are bringing and have brought these activities about.

In making an analysis of this sort, therefore, we are required to answer the following types of questions from a physical standpoint: (a) What is the current weather-situation? This implies a static description. (b) What are the current weather-activities? This implies a dynamic description. (c) What have been the activities in the entire meteorological field since the preceding observations? This too implies a dynamic description. Finally, (d) what are the causes,

their nature, intensity, etc., which have been underlying the past and present weather-situations and activities? This implies more than a dynamic description; it implies the expression and evaluation of functional relationships between the causes and their effects.

From the viewpoint of the practicing meteorologist, the answers to the last question are of fundamental importance since as a rule they form the connecting link between physical analysis and weather-prediction, the field of which presents a vast problem in itself. Here, questions such as the following must be answered: (1) What will be the weather-situation at stated times in the future? (2) What will be the weather-activities between and at these stated times? Owing to our imperfect knowledge of the atmosphere and its workings, these questions imply others which the forecaster must ask himself, explicitly or otherwise: (3) What are the possible and probable causes which may operate to change a given weather-situation? (4) What is the efficacy of each of these causes? (5) What are the respective probabilities that the causes will operate between certain limits of effectiveness? It is obvious that the obtainment of a reliable forecast on a physical basis requires a correct answer to these questions and therefore also a correct physical analysis.

The customary method of determining whether a given cause has operated is inductive--that is, data representing the initial and final conditions involved in a change are obtained, and the initial conditions when substituted in the functional relation connecting the given cause and the specified kind of effect will give the final conditions in question both qualitatively and quantitatively. From a sufficient number of verifications by this procedure, we may tentatively at least infer that the cause under consideration is the one which is producing the effects under discussion. Moreover, if we know the conditions obtaining at different times, the functional relations may possibly be used in an inverse manner to determine the magnitudes, directions, etc., of the operating causes. It should thus be clear that successful analyses and forecasts by physical methods imply the application of an inductive-deductive method of studying meteorological data.

The practical problem in daily meteorological work is to present the data regarding current and past weather-situations and activities in such a way as to render the physical analyses in a clear and expeditious manner most readily applicable to the problem of weather-prediction. From what we have already stated, this necessitates that the presentation of data be made in intimate conjunction with the various basic relationships which may connect them so that the relationships may be tested to verify the causes, or that they may be evaluated to disclose the strengths, etc., of the causes, or that both these things may be done.

To proceed with the problem at hand, it is necessary to consider all the basic relationships involved in the various atmospheric processes. We may begin with a general approach and consider first the branches of physics which afford us such relationships, namely:

(1) Heat--(a) Thermodynamics
(2) Mechanics--(a) Dynamics; (b) Hydrodynamics
(3) Light (radiant energy)
(4) Electricity and magnetism
(5) Physical chemistry

We shall not here attempt to discuss all of these in detail, but shall refer only to some of the more important applications of the first two branches.

The entities with which we deal in physical weather-analysis may be regarded as functions of four coordinates, x, y, z, t--namely, three of space and one of time. The entities in question may be considered as functions of the following five variables, one of which is a vector, namely:

(a) P = barometric pressure
(b) e = vapor-pressure
(c) T = temperature
(d) $\overline{V}$ = vector of wind-velocity (or its three components)
(e) ρ_i = density of { liquid, solid } water; dust and other fine suspended solid or liquid matter, not water; hygroscopic nuclei; ions

From these variables we may compute a number of entities useful in physical weather analysis, for example:

(1) ρ_0 = absolute density of atmospheric air
(2) ρ = density of moist air, excluding suspended matter
(3) w = density of water-vapor
(4) s = specific humidity
(5) p' = partial pressure of dry air
(6) e_s = saturation vapor-pressure
(7) r = relative humidity
(8) s' = mixing ratio
(9) d.p. = dew-point
(10) T' = virtual temperature
(11) θ = potential temperature
(12) θ_d = partial potential temperature
(13) θ_E = equivalent potential temperature
(14) T_E = equivalent temperature
(15) φ' = specific entropy of dry air
(16) φ'_w = specific entropy of water-vapor
(17) φ = specific entropy of moist, unsaturated air
(18) φ_S = specific entropy of saturated air
(19) θ'' = wet-bulb potential temperature
(20) $\vec{v}\rho$ = specific momentum of moist air
(21) $\vec{v}_w$ = specific momentum of water-vapor
(--) and other entities

From these derived entities and the primary variables already given we may determine a number of functions related to the coordinates of space and time. For example, we can compute the various gradients such as those of temperature, pressure, etc., and further we can compute derivatives with respect to time if continuous, or nearly continuous, observations of the meteorological elements are available.

After obtaining all the functions and their space- and time-derivatives, it is necessary to represent them in some convenient manner. This is usually done by plotting the elements or the pertinent functions in question on charts to indicate the horizontal or vertical distribution thereof. (The spacial distribution of a meteorological element is called the field of that element.) Thus we may contemplate a number of fields of the respective elements as in the case of the ordinary synoptic chart. Since time must also be considered, we are confronted with the problem of representation of a fourth coordinate. This is usually done by comparing two charts representing conditions at definite time-intervals apart. However, in some cases time may be used as a coordinate on a chart.

The problem of representation of data on charts may be attacked from a more general viewpoint than that just discussed. Let us consider a number of elements or functions thereof denoted by the symbols v_i, v_j, v_k, etc. and the coordinates x, y, z, t. In a chart, where we are confined to two dimensions, we may in general plot one variable as a function of another, or we may plot one variable as a function of two others. In the former case, we get the combinations v_i x, v_i y, v_i z, v_i t, etc., or $v_i v_j$, $v_i v_k$, etc. In the latter case, we get the combinations v_i xy, v_i xz, v_i yz, v_i xt, v_i yt, v_i zt, etc., and v_i xv_j, v_i yv_j, v_i zv_j, v_i tv_j, etc., and finally v_i v_j v_k, etc. Thus a considerable number of combinations are available. If we employ three-dimensional models, the number is greatly increased.

The general case, last referred to, appears to be most interesting. Suppose observations of the necessary elements are available over space and time. Then for each point of space-time we have values of corresponding elements or functions thereof. Let us select any two coordinates from the available ones: x, y, z, t, v_i, v_j, v_k, etc. Then of the remaining coordinates, elements, or functions, we may allow one or more specified ones to vary, but at the same time keep the others constant. The condition that certain specified arguments are constant, which we have imposed, in general determines the corresponding space-time coordinates and hence also the corresponding values of the two coordinates selected for the chart. We may then plot the corresponding values of these coordinates as points on the chart in question, identifying them in some way with the coordinates x, y, z, t, if necessary. If the specified constant arguments (parameters) are given different fixed values, we obtain corresponding sets of points or different curves passing through these points on the charts. Suppose that the two coordinates of the chart are the independent variables of one or more functions, then we may construct families of curves passing through all points on the chart for which the function (or functions) remain constant at different values. Thus, now having on the chart both the plotted points or curves first referred to and the family (or families) of curves of the function (or functions) last referred to, we may compare the two sets of curves directly and hence possibly discover the implicit relation of the two coordinates of the chart under given assumed conditions in the

meteorological field. For example, on an adiabatic chart, we have pressure and temperature (P, T), as coordinates. Keeping y = latitude, t = time, and s = specific humidity, constant, but allowing x = longitude and z = height to vary, we determine the values of (P, T) corresponding to the intersections of a circle of latitude with the various surfaces of constant specific humidity and construct curves on the chart from the sets of values (P, T) thus found. Since θ = potential temperature is a function of (P, T), we have printed curves of constant potential temperature (adiabats) on the chart. Now finally we may compare the constant specific-humidity curves with the adiabats. If some sections of the respective curves run parallel to one another, this may possibly be interpreted as indicating the tops of layers of subsidence. This approach to the presentation of data offers considerable room for development.

Coming again to the problem of meteorological data and its presentation, there remains the possibility of exploiting the electrical, mechanical, and optical instruments and methods which have been developed in past and recent years. Since physical methods presuppose numerical characterization, and since the instruments in question are eminently adapted to operations involving numbers, mechanisms may be devised to compute the functions required in physical weather-analysis, and moreover, to represent them in convenient form. It is not impracticable for a set of devices to be developed whereby the data received by telegraph or teletype may be placed into a keyboard not unlike that of a typewriter or linotype-machine and have the computations performed automatically and the results thereof printed on a chart or represented in some electrical, mechanical, or optical fashion. Furthermore, such difficult questions as convergence or divergence of air may be dealt with in this way so that, for example, in the optical method of representation areas of convergence would be marked by intense illumination and areas of divergence by feeble illumination. In the electro-mechanical method of representation the approximate amount of vertical transport per unit-area per unit-time in certain regions may be indicated numerically by pointers moving over dials similar to voltmeters. (Opportunity is lacking here to indicate how this may be accomplished.)

Since time is the essence of the problem for the practicing meteorologist and since data of the sort just cited are of great importance in physical weather-analysis and forecasting, we consider the main hope of meteorology to lie in the extension of observations in three dimensions, and the application thereof to physical weather-analysis through the medium of modern mechanical and electrical methods.

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THE HURRICANE-WARNING SERVICE AND ITS REORGANIZATION

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Tropical cyclones are the meteorological monsters of the sea. No other type of ocean-storm approaches them in violence and destructiveness, nor in the persistency with which they maintain their form and force. It is a rare thing for one of them that has fully developed to dissolve and disappear over water-surfaces in the tropics. With few exceptions they continue as violent storms until they strike land or pass out of the tropics. They are called hurricanes when they occur in the Atlantic Ocean, Gulf of Mexico, Caribbean Sea, and the Pacific Ocean off the coast of Central America and Mexico; they are known as "typhoons" in the China Sea, as "baguios" in the water-area of the Philippines, and as "cyclones" in the Bay of Bengal and other portions of the Indian Ocean. By whatever name they are known and wherever they occur they strike terror into the hearts of seamen and of people who reside along the low-lying shores subject to their visitation.

No person or organization can surely be credited with being the first to engage in a systematic forecasting program for the purpose of giving warning of the approach of hurricanes. William Reid began his studies of them when on duty on the Island of Barbados in 1831. His work published in 1838 is still held in esteem as a book of reference, but there is little ground for believing that Reid attempted prognostications. His efforts in the main were confined to studies of hurricanes, to plotting of their courses, and to formulating his "law of storms" including rules for mariners to maneuver so as to avoid their centers.

Perhaps the credit for the first warning might be due to Father Benito Vines, who for many years was associated with Belen College at Havana. It is known that in 1870, when Father Vines became director of the College, he began to grapple with the problem of fore-warning the people of the advent of hurricanes which threatened them. Before that time the inhabitants of Cuba were accustomed to hear of these phenomena only upon their near approach. This was the same year that

our Congress made appropriations for organizing a national meteorological service, control of which was vested in the Signal Corps of the Army (later transferred to the Agricultural Department as the Weather Bureau). The Signal Service was scarcely in position to issue hurricane-warnings until August 6, 1873. On that date arrangements for securing daily weather-reports by cable from Cuba and other islands of the West Indies went into effect with receipt of observations from Havana. Daily reports from Kingston began September 18, and from Santiago de Cuba on September 29 of the same year. Plans for obtaining reports from Puerto Rico, Guadeloupe, and Barbados did not materialize that year as was expected.

The meteorological service of the Signal Corps did not begin to function until 1870, but almost from the beginning the need for issuing warnings of hurricanes to the people along our southern coasts was recognized and also that this could be accomplished only by obtaining current observations from islands in the West Indies. Plans for obtaining such observations were discussed in the reports of the Chief Signal Officer for the fiscal years 1872, 1873, and 1874.

Father Vines had nearly three years' start on the Signal Service in organizing his hurricane-warning service. According to one of his commentators (Rev. Walter M. Drum, S.J.), the earliest authenticated date on which he issued a warning was September 11, 1875, but it seems likely that he did so prior to that time. There too is uncertainty as to the date of the first hurricane-warning issued by the Signal Corps. Father Vines is generally conceded to be the first meteorologist to forecast hurricanes by observation of the upper as well as of the lower clouds; also, he was the first to announce that the place of formation and direction of movement of hurricanes change as the season advances. The August, 1873, issue of the Monthly Weather Review refers to a forecast issued on August 23, 1873, of stormy weather for the New England and Middle Atlantic coasts "with cautionary signals at Cape May, New York, and New London." This article contains a statement to the effect that the storm was of tropical origin, that it was by far the worst one since the establishment of the Signal Corps and that it "did not occur within the limits of our stations." It is a safe deduction that August 23, 1873, was the date of the first warning issued in connection with a storm of tropical origin but it would not be proper to claim that it was a hurricane-warning because the storm was extratropical when the warnings were promulgated.

Whether or not Father Vines issued the first hurricane-warning, justly he is placed in the front rank of those who have contributed to our knowledge of tropical storms and for his untiring efforts to develop means for forecasting them.

Father Vines' hurricane-forecasting studies were in four directions: (1) "To find some sign or group of signs that would invariably prove the existence of a cyclone while it was yet at a great distance from the observer; (2) to get bearings in regard to the whirlwind, that is, to determine what part of the horizon it was coming from; (3) to locate the trajectory or curve along which the cyclone would move and to do this in time for the observer to betake himself to a safe distance from that fatal curve; (4) to determine the distance of the hurricane from the observer, its intensity, area, and velocity."

A serious set-back in the development of the hurricane-warning service occurred in 1876 because of discontinuance of observations from the West Indies due to lack of funds for cabling, but this difficulty was partially overcome by the generosity of the cable-companies in granting reduced rates of one-third to one-half of commercial rates.

In 1881 the reports from the West Indies again were suspended partly because of lack of funds but principally because of "doubt being thrown on the legality of spending any part of the appropriations in maintaining a station outside of the limits of the United States." This difficulty appears to have been removed before the next season began. At that time six West Indian reports were being received, namely, Barbados, Guadeloupe, Havana, Kingston, Santiago de Cuba, and St. Thomas. In 1888 or 1889 other reports--Puerto Rico, Santa Cruz, and Antigua--were secured through the newly organized Cuban Meteorological Service. From that time onward until the outbreak of the Spanish-American War the records do not divulge any material change in the general operating plans of the hurricane-warning service.

In 1898 there was what may be termed the first reorganization of the hurricane-warning service. It was due to the Spanish-American War. Prior to that time warnings had been confined to our own coastal areas, although there was courtesy exchange of hurricane-information between the Weather Bureau and the Cuban Meteorological Service and Belen College.

Since 1873 observers at West Indian points had been local residents. They were paid for taking the observations but were not subject to any official control by our Government. When war was declared in 1898, it was recognized at once that the hurricane-warning service on the old

basis would be wholly inadequate to protect the large fleet of naval craft, of transports, and of United States merchantmen operating in the waters subject to hurricane-visitations. Accordingly, a bill was drafted and submitted to Congress on June 18, 1898, authorizing the Weather Bureau to establish and operate observing stations throughout the West Indies and along the shores of the Caribbean Sea. The Act making appropriations for the service was not approved until July 7, 1898. Permission had to be obtained from various governments for placing trained observers and citizens of the United States at places from which observations were desired. It was obvious that only those whose loyalty and efficiency were beyond question could be given responsibility in such an important undertaking. Much of this preliminary work was done before the appropriation act was passed on July 7, 1898. By vigorous action the first party was started on July 22, 1898, and before the middle of August trained observers of the Weather Bureau had opened stations at Kingston (Jamaica), Port of Spain (Trinidad), Willemstad (Curacao), Santo Domingo (Santo Domingo), and Santiago de Cuba. Before the middle of September additional stations were operating at Basse-Terre (St. Kitts) and Bridgetown (Barbados). The Weather Bureau forecasting-center in the West Indies was located at Kingston (Jamaica).

The war soon was over--in fact, before there was opportunity to issue warnings to our combatant fleet. Nevertheless, there never was question as to the wisdom of the action to provide means for guarding our ships against hurricanes, one of which unannounced might have caused more damage than the entire Spanish fleet. Notwithstanding the cessation of hostilities it was decided to complete the original organization plan. Stations were established at Ruseau (Dominica), at San Juan (soon after Puerto Rico came into United States control), and at Colon. Original intentions to place stations at St. Thomas and Barranquilla were abandoned and the station at Colon was closed early in 1899. Headquarters of the forecasting service was transferred to Havana on February 1, 1899. At the same time plans were perfected for giving all parts of the West Indies and ships of all nationalities the benefit of the hurricane-warning service of the Weather Bureau. This responsibility has international recognition to this day.

Within a year after the declaration of peace on December 12, 1898, observers began to be withdrawn from the West Indian stations as fast as capable local persons could be trained and qualified to take the observations. In 1902, at the termination of the American occupation, the hurricane-forecasting work for the West Indies was transferred from Havana to Washington. All Weather Bureau employees were withdrawn except one who remained for the purpose of completing the substitution of local observers for those sent from the United States. A forecast-center for the issuing of hurricane-warnings and advices for Puerto Rico and contiguous areas was established at San Juan on June 1, 1919.

Steady improvements were made in the efficiency of the service after the Spanish War. The largest factor in this improvement is due to development of the radio. It has added tremendously to the field of observation. Far greater dependence now is placed on ship reports than on observations from island-stations. Ships make regular contributions of two observations a day and additional ones when needed. Last year more than 21,000 observations were received from ships in the southern portion of the North Atlantic, of the Gulf of Mexico, and of the Caribbean Sea during the six months which constitute what is known as the hurricane-season.

A third epochal change in the hurricane-warning service will occur on July 1, 1935. Changes as contemplated on that date are made possible by an item of $80,000 contained in the Weather Bureau portion of the Agricultural Appropriation Bill for the next fiscal year.

Since the beginning of the hurricane-warning service in 1873, warnings and advices concerning tropical storms have been issued from Washington, except for the short period during the Spanish War--when the West Indies area was handled from Kingston and Havana--and the service rendered at San Juan since 1919. Under the new reorganization effective on July 1, 1935, no warnings of tropical storms will be issued from Washington except for such as have moved north of latitude 35° north. It is believed that more expeditious, satisfactory, and efficient service can be rendered from forecast-centers located nearer to the scene of action than is Washington. Strictly speaking, after July 1, 1935, there will be three hurricane-warning centers as follows: San Juan--Caribbean Sea and islands east of longitude 75° west and south of latitude 20° north; New Orleans, Louisiana--that portion of the Gulf of Mexico and its coasts west of longitude 85° west; and Jacksonville, Florida--remaining portions of the Atlantic, Caribbean Sea, and Gulf of Mexico areas, islands, and coasts south of latitude 35° north.

Jacksonville also will be a district forecast-center to include the states of North Carolina, South Carolina, Georgia, and the Florida Peninsula. From that center will emanate all daily weather-forecasts, warnings of cold waves, frosts, weekly outlooks, etc., for the states named in addition to storm- and hurricane-warnings. At present all of this work is being done at the Washington forecast-center. Jacksonville also will take over from the Washington center, twice daily, wind- and weather-forecasts for the coastal and contiguous ocean-zones, Hatteras to Jack-

sonville, Jacksonville to the Florida Straits, the Eastern Gulf of Mexico (east of longitude 85° west), and the Western Caribbean Sea (west of longitude 75° west).

New Orleans is now a forecast-center for extreme northwest Florida, Alabama, Mississippi, Arkansas, Oklahoma, and Texas, and storm-warnings for the Gulf Coast from Apalachicola westward to Brownsville. Its principal additional work, to be transferred from the Washington center, will be the hurricane-service for the area as heretofore described; also daily wind- and weather-forecasts for the Middle Gulf of Mexico (between longitude 85° west and 90° west, north of the Yucatan Channel) and for the Western Gulf of Mexico (west of longitude 90° west) will emanate twice daily from New Orleans instead of from Washington.

The reorganization program involves material changes in the collection of observations from ships. Under existing arrangements observations are secured regularly twice a day throughout the year by radio from a limited number of selected ships in the Atlantic, in the Gulf of Mexico, and in the Caribbean Sea. These reports are now transmitted only to Washington. On and after July 1, 1935, the selected ships when south of latitude 35° north will transmit their observations addressed both to Washington and to Jacksonville. Those north of that line will continue to report only to Washington. Another class of ships, known as cooperative, supplies observations only during the hurricane-season, June to November, inclusive. Heretofore service from this class of vessel consisted of two observations a day, taken at 00:00 and 12:00 G.C.T., and containing only the Universal group of data (day of week, octant of globe, latitude, longitude, direction of wind, state of weather, wind-force, barometric pressure, visibility, and temperature). After July 1, and during the period June 16 to November 15, inclusive, they will take two additional observations at 06:00 and 18:00 G.C.T., making four in all. Observations from cooperative ships will contain the Universal data group and also a supplemental group (swell, clouds, temperature-difference between air and water, ship's course, barometer-change, and past weather). Cooperative ship reports will be addressed only to Jacksonville.

A system of direct calls for special observations from ships when a hurricane is in progress was inaugurated in 1934. It proved to be successful and it will be continued in the reorganization program. This plan, briefly stated, is as follows: The southern portion of the Atlantic, the Gulf of Mexico, and the Caribbean Sea is divided into five-degree squares which are numbered. When a hurricane is known to be in progress, commercial radio stations at Galveston, Port Arthur, Tampa, West Palm Beach, and Ensenada (Puerto Rico) are informed of the areas (squares) from which special ship reports are desired and the time the observations should be taken. Operators at these stations contact all ships in the specified squares and ask that the observations be radioed to a specified Weather Bureau forecast-center. In this way many valuable reports are secured which otherwise would not be available.

Another feature, not strictly new but on a more systematized basis, will be cooperation with the United States Coast Guard, whereby weather-observations, including data on swells and tides, will be obtained from Coast Guard life-saving stations. As a rule, observations from Coast Guard stations are not needed until the storm has approached within a few hundred miles of the coast. They will be collected by telephone, telegraph, and radio and speedily will be made available to the forecast-centers at New Orleans and Jacksonville. In a similar way there will be cooperation with Coast Guard ships both in forwarding observations taken on board and also in collecting observations from other ships. By a like plan reports from Coast Guard stations, from Cape Fear River northward to the Delaware Breakwater, will be secured for the forecasters at Washington.

An incidental but important part of the program will be the exchange of warnings and advices issued at Washington, Jacksonville, and New Orleans so that each may have knowledge of what the others have done and thereby avoid conflict and confusion.

The Weather Bureau maintains storm-warning display-stations at numerous ports along the coasts affected by hurricanes. A systematic plan for obtaining special weather-, tide-, and swell-observations from those places is a part of the program.

At the present time all hurricane-warnings and advisories are included in a bulletin specially designed for the use of masters of ships at sea and are broadcast twice daily through the Naval radio station at Arlington, Virginia. This bulletin is copied by other Naval stations and rebroadcast so that all ships in waters subject to tropical storms are warned. This service will be continued. Warnings issued from San Juan, Jacksonville, and New Orleans will be telegraphed to Washington for inclusion in the bulletin. In addition, a special bulletin containing weather-information, forecasts, hurricane-warnings, etc., will be broadcast twice daily during the hurricane-season and on fixed schedules from the Naval radio station at Key West, Florida. It is expected that commercial radio stations will cooperate similarly in the distribution work.

A unique and important feature of the reorganization will be a teletypewriter set-up during the five active hurricane months. This system is designed for speedy collection of observations from life-saving and storm-warning stations, the distribution of land and ship reports from one forecast-center to the other, including intervening first-order stations, and immediate dissemination of warnings and advices to the entire coastal area. This teletype-circuit will connect the Weather Bureau forecast-centers at Jacksonville and New Orleans and at its offices at Tampa, Miami, Key West, Pensacola, Mobile, Port Arthur, Houston, Galveston, Corpus Christi, and Brownsville. The teletype-circuit will operate 24 hours a day, every day in the week, including Sundays and holidays, and will be used exclusively by the Weather Bureau.

A forecaster will be on duty night and day at Jacksonville and New Orleans and trained observers will be on watch constantly at all the other offices having teletype-installations. In this way advantage will be taken of every weather-report that has significance, the forecaster will be in continuous touch with the local Weather Bureau officials, and through the latter the newspapers and the public will be kept fully and promptly informed.

U. S. Weather Bureau,
Washington, D. C.

A RELATION BETWEEN TEMPERATURE AND CYCLONE-FREQUENCY IN THE TROPICS

I. R. Tannehill

Variations in the mean monthly temperatures in the tropics are slight, especially in island and coastal sections and over the open oceans. The annual range in monthly mean temperatures is of the order of one to two degrees, Fahrenheit, in some equatorial regions. This variation follows roughly the annual changes in insolation, with a lag similar to that which characterizes the more pronounced seasonal variations of higher latitudes.

At the equator there is a double period in the variation of intensity of insolation with maxima at the time of the equinoxes. There is a tendency toward the development of two temperature-maxima, one following each equinox, but the variation is so small that it is often masked by the effects of changes in cloudiness, wind-direction, and rainfall.

The annual variation in the angular distance of the Sun from the zenith at noon, on the equator, and at 5°, 10°, 15°, 20°, and 25° north of the equator, is shown in Figure 1. The angular distance from the zenith is given in Figure 1 without regard to whether the Sun is north or south of the zenith. Insolation received at the Earth's surface in these latitudes varies as the Sun's declination changes but the angle of incidence is not the only influence--the varying distance of Earth from Sun, for example, is one of the factors. So far as the resultant temperature of the surface-air is concerned, there are many others. However, the curves shown in Figure 1 will serve to indicate roughly the nature of the variations in insolation. The maximum

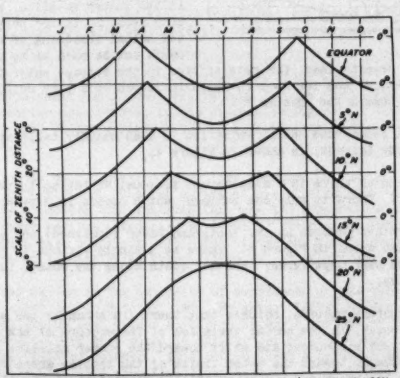

FIG. 1—ANNUAL VARIATION SUN'S ANGULAR DISTANCE FROM ZENITH AT NOON

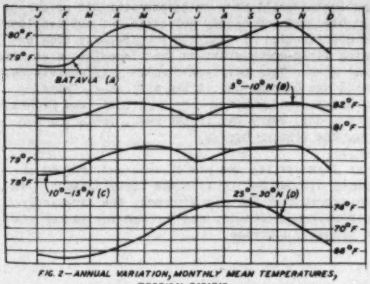

FIG. 2—ANNUAL VARIATION, MONTHLY MEAN TEMPERATURES, TROPICAL PACIFIC

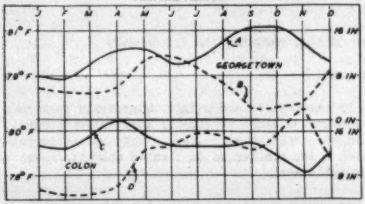

FIG. 3—MEAN MONTHLY RAINFALL(---) AND TEMPERATURE (——)

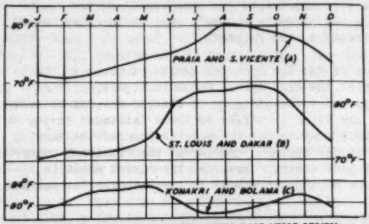

FIG. 4—MONTHLY MEAN TEMPERATURES, CAPE VERDE REGION

intensity of insolation occurs when the Sun is at the zenith at noon and intensity diminishes as the Sun departs from the zenith, either northward or southward.

The annual variation in monthly mean temperatures is shown in Figure 2 for the following: Curve A for Batavia; curve B for the Tropical Pacific, 5° to 10° north latitude--average of Palau, Yap, Solomon Island, and two stations on Marshall Islands; curve C for the Tropical Pacific, 10° to 15° north latitude--average of Sumay and Apia together with averages in the 5-degree square, 10° to 15° north and 160° to 165° west; and curve D for the Pacific, 25° to 30° north latitude--mean of records at Midway and the 5-degree square, 25° to 30° north and 140° to 145° west. These curves reflect the effects of variation in insolation in the respective latitudes.

An example of the effect of rainfall is shown in Figure 3. At Georgetown, British Guiana, about 7° north latitude, the autumnal temperature-maximum is the more pronounced one, evidently because there is much less rainfall at that season. At Colon the reverse is true, evidently because more rainfall occurs in the latter half of the year. The temperature-minimum in November at Colon coincides with the rainfall-maximum there.

Speaking of the water-temperatures in the Caribbean Sea, McDonald and Showalter [1] noted "a distinct retardation in the average rate of temperature-rise after May, as if there were a tendency toward a small secondary minimum about July." They gave the following explanation: "The rapid rise in temperature in the Caribbean in May coincides in time with the vertical passage of the Sun northward toward the tropic of Cancer. At the summer solstice, however, the Sun is only about 5° to 10° north of this area, and the actual lessening of radiation-intensity could not be such as to permit any cooling by outgoing radiation. Nevertheless, the rate of rise in the average water-temperatures is lessened at the summer solstice, and the rate is again increased at a time coincident with the return passage of the Sun toward the equator."

From a record of 21 years, the annual variation in mean monthly temperature at Praia and S. Vicente, in the Cape Verde Islands, is shown in Figure 4.

In the Cape Verde region there is a more marked seasonal variation in temperature than is found nearer the equator. There is only one maximum, which occurs in September.

Mean monthly temperature records at St. Louis and Dakar (combined) and at Konakri and Bolama (combined) are also shown in Figure 4. There is a single maximum in the curve for St. Louis and Dakar which are near Cape Verde. Farther south along the coast, for Konakri and Bolama, there are two maxima.

The foregoing temperature-records indicate that there are normally two maxima, following some time after the equinoxes, in the annual variation of temperature at the equator and that these two maxima become less pronounced and shift toward the summer solstice with increasing distance away from the equator toward the outer limits of the tropics where they merge into a single maximum with some lag after the summer solstice. The effects of insolation are, however, often masked by the influence of rainfall and other phenomena.

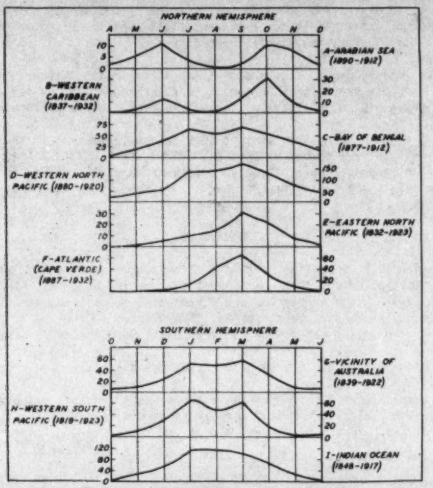
NORTHERN HEMISPHERE
A M J J A S O N D
A-ARABIAN SEA (1890-1912)
B-WESTERN CARIBBEAN (1887-1932)
C-BAY OF BENGAL (1877-1912)
D-WESTERN NORTH PACIFIC (1880-1920)
E-EASTERN NORTH PACIFIC (1932-1933)
F-ATLANTIC (CAPE VERDE) (1887-1932)
SOUTHERN HEMISPHERE
O N D J F M A M J
G-VICINITY OF AUSTRALIA (1939-1922)
H-WESTERN SOUTH PACIFIC (1919-1923)
I-INDIAN OCEAN (1848-1917)

FIG. 5—MONTHLY FREQUENCY OF TROPICAL CYCLONES

The monthly frequencies of tropical cyclones in various parts of the world are shown in Figure 5. In several regions there are two maxima, the curves corresponding roughly with those of insolation and temperature. In the northern hemisphere there is a secondary minimum in August in some localities; in the southern hemisphere the secondary minimum occurs six months earlier in February.

It is obviously impossible to ascertain the point of origin of many of the tropical cyclones that have been charted in the Gulf of Mexico, in the Caribbean Sea, and in the Atlantic Ocean. For the purposes of this discussion, I have divided them as far as possible into two classes--Atlantic and Caribbean. In the Atlantic class I have placed all those which appear to have come from the Cape Verde region or from the Atlantic eastward of the West Indies. In the Caribbean class I have placed all which apparently came from the Western Caribbean. There are very few, if any, cases of definite origin in the Eastern Caribbean, according to Mitchell [2]. Charted tracks which afford no clue whatever as to the place of origin have been omitted from the tabulation.

The Atlantic type has a single maximum of frequency which occurs in the month of September, while the Caribbean type shows two maxima, one in June and the other--the principal one--in October. These frequencies are included in the diagram in Figure 5. Cyclones have been recorded in other months in some of these regions but in much smaller numbers than in the months included in the diagram.

The secondary minimum of cyclone-frequency lags somewhat farther behind the summer solstice than does the temperature-minimum. The two maxima of cyclone-frequency which appear in some regions are separated by a shorter time-interval than are the temperature-maxima near the equator. However, in each of these regions frequented by tropical cyclones we have grouped together a number of cyclones which have doubtless originated at various distances from the equator and under various conditions of insolation at those latitudes, as illustrated in Figure 1.

There are also two maxima in the intensity of hurricanes of the Atlantic (including the Gulf and Caribbean), according to Mitchell [2]. He says: "After noting the decided decrease in the number of tropical storms that attain hurricane-strength during the latter half of September, it is rather surprising to find that there is another period of maximum frequency of these severe storms during the first half of October. This period shows a total of nearly twice as many as the latter half of September, more than five times as many as the latter half of October, and nearly two-thirds as many as the first half of September."

This second period of maximum storm-intensity in early October is undoubtedly due to an increase in the frequency and intensity of cyclones of the western Caribbean at a time when the activity of the Atlantic type has greatly diminished.

Conclusion--The double period in the annual variation in insolation in equatorial regions is accompanied by a double variation in temperature which appears to be the cause of the two maxima of cyclone-frequency as recorded in the average year in some tropical regions.

Acknowledgment--Data showing frequency of tropical cyclones used in this discussion were secured from publications by a number of writers, chiefly from Mitchell [2], Visher [3], and Newnham [4]. Temperatures at land-stations were taken from published and unpublished climatological studies by Reed [5], and ocean-temperatures were secured from the Marine Division of the Weather Bureau.

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A THEORETICAL STUDY OF WIND-VELOCITY AND WIND-DIRECTION IN CURVED AIR-CURRENTS

B. Haurwitz

(Abstract)

The problem of wind-distribution in the vertical has so far been treated only for straight-line flow. In this case we have equilibrium between the pressure-gradient force, the Coriolis force, and the frictional force, if we assume steady motion. The solution is the well-known Ekman spiral.

In many instances, however, the simple assumption of straight-line flow does not hold. In the inner part of cyclones and especially in tropical cyclones the curvature of the isobars is large enough to give an appreciable centrifugal force which enters in the balance of forces. In anticyclones the influence of the centrifugal force is probably much smaller since the winds in the interior are feeble.

We assume that the kinematic coefficient of viscosity ν is constant, that the motion is steady, and that the complex horizontal velocity vector $w = v_r + iv_\theta$ is proportional to the distance from the center r

$$w = f(z) \cdot r$$

These assumptions are necessary in order to obtain an exact solution, without approximational methods. The pressure gradient may be purely radial and also proportional to the distance from the center and constant with elevation

$$-(1/\rho)(\partial p/\partial r) = -(k/\rho)r$$

an assumption which is known not to cause a great error. We obtain then

$$(w^2/r) + 2i\ell w = -(k/\rho)r + \nu(d^2w/dz^2) \qquad (1)$$

where $\ell = 7.29 \cdot 10^{-5} \sec^{-1} \sin\varphi$ and φ = latitude. As boundary-conditions we assume that the wind approaches the gradient-wind for great heights asymptotically and that it vanishes at the ground.

The more adequate surface-condition, that the stress at the ground is proportional to the wind, will be treated later. We write for the sake of brevity

$$x = [\ell^2 + (k/\rho)]^{1/4}/\nu^{1/2}(z/2)$$

Where d is a constant defined by

$$d = \cosh^{-1}\left\{3\sqrt{\ell^2 + k/\rho} \;/\; [\sqrt{\ell^2 + k/\rho} - \ell]\right\}^{1/2}$$

we obtain as solution for (1) the radial velocity

$$v_r/r = -6\sqrt{\ell^2 + k/\rho}\ [\sin 2x \cdot \sinh 2(x + d)]/[\cos 2x + \cosh 2(x + d)]^2 \qquad (2)$$

and for the tangential velocity

$$v_\theta/r = \sqrt{\ell^2 + (k/\rho)} - \ell - 6\sqrt{\ell^2 + (k/\rho)}\ [1 + \cos 2x \cosh 2(x + d)]/[\cos 2x + \cosh 2\,(x + d)]^2 \qquad (3)$$

(2) and (3) hold for cyclonic pressure distribution, (k/ρ) greater than 0. From (2) it is seen that we have inflow towards the center. The similar solution for anticyclonic pressure-distribution will not be given here.

To give a numerical example let us assume that we have a gradient wind of 20 meters/sec in 30° latitude. With an average density of $1.1 \cdot 10^{-3}$ ton/meter^3, that would correspond to a gradient of 1.21 mm/100 km for straight isobars. In the cyclonic system of isobars let us consider a point 500 km distant from the center. The pressure gradient must here be 1.87 mm/100 km. For the kinematic viscosity ν we assume 50 meters^2/sec, a fairly high value which seems justified for winds of this intensity. Figure 1 gives the distribution of the wind-vector. The abscissa represents the component normal to the pressure gradient, v for straight-line flow, and v_θ for curved flow. The ordinate gives the component parallel to the gradient, u for straight isobars, v_r for curved ones. It is drawn downward since we have flow towards the low pressure. The broken line represents the case of straight isobars and the full one represents that of curved isobars. The figures beside the curves give the height of the points in meters. The curves are very similar to each other. However, if we consider the heights, we see that for the same elevations the wind in the case of curved flow is much stronger than for straight flow. The gradient wind-velocity of 20 meters/sec is reached at about 1200 meters for curved flow, but not till about 1700 meters for straight flow. The angle between actual wind and gradient wind is 45° toward the low pressure at the ground in both cases. It decreases more rapidly for curved than for straight flow and vanishes in the first case at about 2500 meters, in the second case at about 3500 meters. All this shows that the influence of the centrifugal force in a cyclone tends to make the wind reach the gradient-wind in a lower altitude than in the case of straight isobars.

We can see that directly from our formulae. The depth of frictional influence is given in the straight-line flow by

$$D = \pi\sqrt{\nu/\ell} = 3520 \text{ meters with our figures}$$

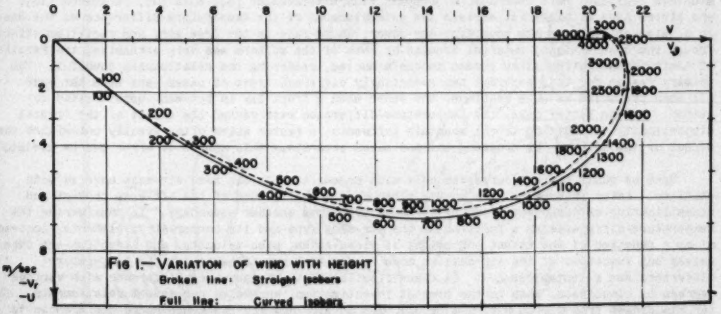

FIG 1.—VARIATION OF WIND WITH HEIGHT
Broken line: Straight isobars
Full line: Curved isobars

in our case by

$$D = \pi\sqrt{\nu/(\ell^2 + k/\rho)^{1/4}} = 2530 \text{ meters with our figures}$$

The influence of the centrifugal force is thus similar to an increase in latitude or a decrease in

Owing to this faster approach of the wind to the gradient-wind in the cyclones the flow of air across the isobars toward the low pressure is here smaller than for straight isobars. This can easily be computed as the real part of the integral

$$\int_0^\infty w\rho \cdot dz$$

We find that in our numerical example 9.3 tons per second are transported through a vertical surface of the height of the atmosphere and a base-line of one meter, while the corresponding value for straight isobars is 12.93 tons/sec. The total mass-transport across the circular isobar at 500-km distance from the center of the cyclone would thus be $29.2 \cdot 10^8$ tons/sec.

The application of these results to tropical and extratropical cyclones will be dealt with later.

[The complete paper will be published in Gerland's Beiträge zur Geophysik.]

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FREE-AIR TEMPERATURES FROM OBSERVATIONS ON MOUNTAIN PEAKS WITH APPLICATION TO MT. WASHINGTON

Irving I. Schell

Introduction

The purpose of this paper is to treat, in the light of new principles (air-mass concept), the problem of temperature-differences between mountain tops and the free air at the same level and to indicate an approximate method for obtaining free-air temperatures from the Mt. Washington observations.

With the development of the air-mass concept of the lower atmosphere, the problem of the temperature-difference between the temperature on mountain tops and that of the free-air at the same level over a point away from the mountain allows a more effective treatment, holding out a promise for free-air temperatures to be derived from mountain observations. In the past the relationship of this temperature-difference with meteorological elements was extensively studied, with the result that a large amount of literature on the subject has been published. In Europe, Schmauss [1], von Ficker [2], and de Quervain [3], to mention a few, and, in this country, Fergusson [4,5] and Clayton [6], have investigated this problem using observations from various mountain regions. More recently, W. Peppler [7], Kleinschmidt [8], Noth [9], Fergusson [10], and others have attempted to explain the establishment of the temperature-difference on the basis of wind-velocity on the mountain, sky-cover, lapse-rate in the free air, and radiation-effects. Though the observational material treated by some of the authors was very extensive, the results of their investigation often showed inconsistencies, rendering the relationship doubtful. The primary reason for this was that two essentially different types of cases--one when the same air-mass prevailed at both stations, the other when a front lay in between--were treated together. In the latter case, the temperature-difference represented the effect of the frontal discontinuity in addition to the mountain influence, a factor which often greatly outweighed the effect of the latter. By treating the two cases separately this source of error can be avoided.

Here we shall concern ourselves only with cases in which the same air-mass covered both stations. Later we hope to take up the other case too. The use of the air-mass concept and classification of cases according to air-mass type gives another advantage. In considering the temperature-difference as a function of the air-mass type and its conservative elements, instead of as a function of the extent and height of cloud-cover, wind-velocity, and direction--in themselves but functions of the air-mass--a more fundamental relationship for the temperature-difference can be established. (A classification of the temperature-difference with various degrees of cloudiness, made in the present investigation, showed no consistent relationship. Thus for cloudiness from 0.0 to 0.3, 0.4 to 0.7, 0.8 to 1.0, and fog the temperature-differences in Centigrade were 6?4, 5?9, 5?9, and 5?2, respectively.)

The need for upper-air data at all times is essential for a better knowledge of the physical processes in the atmosphere and consequently for better forecasts. Continuous records show the exact time important atmospheric changes take place, such as passage of fronts, allowing a better determination of the progress of an approaching air-mass. At the present the only means of obtaining continuous records of the upper atmosphere are mountain observatories. The airplane cannot supply them, firstly because it cannot fly in "bad weather" at a time when observations are most desired, again, because of time-intervals between flights, and finally because of the expense involved.

While mountain observations are restricted to low levels, they can provide, since the most important changes take place in these levels, a picture of conditions in the meteorologically most active stratum. However, as mountain observations do not represent free-air conditions, it becomes necessary to make these observations yield free-air data. This can be done by comparing mountain observations with those on the same level at a point removed, determining the correction-factors, which may then be applied to the observations. The above method was followed in the present work.

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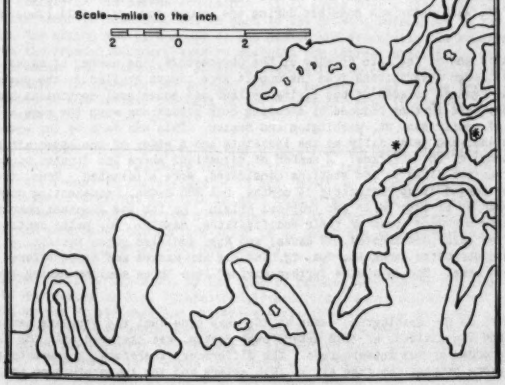
Location of stations

The summit of Mt. Washington (1915 meters above sea-level) on which Mt. Washington Observatory stands, is located in the White Mountains which form a part of the Appalachian Range extending in a northeast-southwest direction, parallel to the coast. Mt. Washington is the highest peak of the Presidential Range, which runs approximately in a north-south direction, and rises about 300 meters above its general height. From the north half portion of the Range another range, much lower in height, runs almost straight west. To the south there is a notch separating the Range from a broken chain of mountains which extends to the southwest. Due to the confining topography of the surroundings, the presence of a strong westerly current will result in forcing the air



from the lower levels up and over the Presidential Range and, if sufficiently strong, also over Mt. Washington (see map). The retardation of an element of air as it is forced upward is small in comparison with the upward acceleration, as is evidenced by high wind-velocities on the summit even in very stable air-masses. This is not surprising. It has been found [11] that generally the wind is intensified on the mountain top when its direction is perpendicular to the direction of the barrier, and that it becomes less strong when the direction of the mountain range is parallel to it. In the first instance, the air not finding a ready avenue of escape will be forced to rise over the barrier and, because of the great pressure-gradient occasioned, will give rise to more or less greater velocities depending on the extent of the confining character of the topography despite the retarding effect of the mountain itself. In the second case where the air can readily go around the range, no air is forced up from the lower levels. On the other hand, the mountain causes a retardation of the flow in the upper level with the result that diminution of the wind-velocity occurs on the top.

The topography in the vicinity of Mt. Washington, as shown by the map, indicates that any strong flow from a general westerly direction will be forced, depending on the horizontal pressure-gradient, to go over the Presidential Range and summit of Mt. Washington. Since, with but a few exceptions, the cases investigated here are with a westerly flow-movement, the assumption can be made that the air is forced upward.

Boston, the point of comparison, is about 132 miles to the south. The large distance is a disadvantage but this is considerably reduced (1) by using observations only during situations when the same air-mass prevailed over both points of comparison (thus affording uniform conditions) and (2) by taking note of the latitudinal temperature-gradient in the free air. We shall return to this question later when the temperature-differences are treated in detail.

The other station (Base-Station) which was operated but part of the time of the period investigated, is located at the foot of Mt. Washington on its west side. It is 790 meters above sea-level and lies well exposed to any westerly flow which precludes the possibility of observations taken there from being influenced by the presence of stagnant pools of air (see map).

Discussion and treatment of observational material

The observational material consists (1) of observations of temperature, pressure, relative humidity, wind-velocity, and wind-direction on the summit of Mt. Washington procured by the fully equipped Mt. Washington Observatory and (2) of records of temperature, pressure, and relative-humidity distribution in the free air over Boston obtained by means of an aerometeorograph carried up for some time by the airplane of the meteorological course of Massachusetts Institute of Technology and during another period by the Army plane flying under the direction of the Institute. In addition to these data, observations obtained at the foot of Mt. Washington (west side) were also used. The period investigated starts with the date of the inauguration of complete and satisfactory observation by the Mt. Washington Observatory, November 21, 1932, and ends with the last day of May 1934 when our investigation got under way. Since the airplane was operated by the Institute only through the "school year," no comparison of free-air condition over Boston with Mt. Washington was possible during the summer and early fall (June to September inclusive).

Because of this and of the late opening of the Observatory, the number of cases studied for fall is small. Although observations from the summit were always available, the number of cases for comparison was reduced because of bad flying weather and occasional mechanical non-fitness of the airplane. They were further reduced by choosing only situations when the same air-mass covered both points of comparison, Mt. Washington and Boston. This was done by the examination of the synoptic maps analyzed twice daily at the Institute and a study of the upper-air data available from the ascents of the airplane. A number of situations where the frontal boundary was not well defined, or was too close to the stations considered, were eliminated. Thus, there were available, for the period of approximately 14 months, but 280 cases, representing continental and maritime air-masses of both polar and tropical origin. By far the greatest number of cases (242) comprise three air-mass types or their modifications, namely: Pc, polar continental, 123 cases; Npc, modified polar continental, 77 cases; and Npp, modified polar Pacific, 42 cases. The other 18 were distributed among Pa, Npa, Tg, and Ntg air-masses and hence offered too few cases to be treated here. The data were further divided into three seasons making in all nine classes.

The temperature on Mt. Washington, taken at the same time that the airplane carrying the meteorograph reached the altitude of 1915 meters over Boston, was compared with the temperature of the free air recorded by the meteorograph. The difference, therefore, represents the actual temperature-difference between the free air at 1915 meters and the temperature on the summit of

Mt. Washington. Since most of the ascents were made early in the morning, the comparison is for conditions in the early morning. This also implies that the effect of insolation was very slight and therefore was not considered here. This fact was especially true during winter.

The relationship of the actual temperature-difference, which we shall denote with the symbol ΔT_1, to other elements is given in tables which in some instances are supplemented by diagrams. The values represent mean temperature-differences for particular conditions, namely, air-mass, season, mean lapse-rate surface to 1915 meters over Boston, wind-velocity on Mt. Washington, etc. Starting with the most general conditions, the cases were then segregated for more specific conditions, and in some instances the process was repeated with slight modification to verify and emphasize the relationship.

The cooling of the mountain being due largely to forced ascent, the difference between the temperature at the summit and that of an element of air raised from sea-level at Boston to 1915 meters could be employed to show to what extent the actual cooling approaches the maximum possible cooling. The evaluation of the fictitious temperature-difference, ΔT_2, was very conveniently made with the aid of the equivalent potential-temperature diagram (Rossby diagram--described by C.-G. Rossby in Thermodynamics applied to air-mass analysis, Mass. Inst. Tech., Met. Papers, v. 1, No. 3, 41 pp., 1932). Tables and diagrams are included, giving the relationship of this fictitious temperature-difference, ΔT_2, to different elements. Finally the difference, ΔT_3, between the temperature which an element of air would have if raised from the Base Station at the foot of Mount Washington (790 meters) to 1915 meters and the observed temperature on Mount Washington, which was evaluated by the same method, is compared with ΔT_2.

The air-masses

A brief discussion of the air-mass types met with in New England is essential in connection with our problem (for a full treatment, see H. C. Willett, American air-mass properties [12]). The air-mass classification was originally developed by T. Bergeron and later applied with modifications by H. C. Willett to the somewhat different air-mass types which are met with in the United States. In our case we shall be concerned with the three principal types which are encountered in the northeastern part of the United States. They are: Pc, polar continental; Npc, modified (transitional) polar continental; and Npp, modified (transitional) polar Pacific.

Winter--The Pc air-mass which originates in the North American Continent from Canada northward over Alaska and the Arctic becomes, in course of a continued stay over a cold snow or ice-covered surface, excessively cold and dry in the lower layers. The almost total absence of winds, and marked stability preclude turbulence, so that the lower strata of this stagnating air-mass continue to get colder and drier, being further reduced in moisture-content by condensation. Protected from intermixture with the moist, warm current from the Pacific by the high mountains to the west, the upper layers retain their coldness and dryness although they are considerably warmer and somewhat moister than the lower layers. This cold, dry, and thermally stable air-mass undergoes deep changes in its course southward. If it moves over a snow-covered surface the thermal stability tends to increase, due in part to the growing subsidence in the air-mass. On the other hand, the mixing set up because of its motion and especially the appearance of cyclonic circulations on the frontal boundary tend to diminish its thermal stability. The lower layers become somewhat warmer and, because of moisture-evaporation which takes place as the air moves southward, less dry. In crossing the Appalachians it becomes mixed in the lower layers, loses some of its moisture, and becomes somewhat warmer. However, when it arrives in New England it is still cold, thermally stable, and dry.

More often the mass of air progresses over a snow-free surface. Then the original characteristics of the air-mass are radically changed; the lower layers become considerably warmer and moister. The air-mass is now designated as Npc, modified (transitional) polar continental. From Table 1 it appears that the Npc type is more than 8° warmer at the surface than the Pc type and contains also more moisture at the 2-km level than the former. The slight increase in stability despite the warming of the surface-layer is no doubt due to a marked increase in subsidence as the air-mass slowly moves over the country.

The Pp, polar Pacific, air-mass, by the time it reaches New England has been extensively modified and is designated as Npp, (transitional) modified, polar Pacific. It is probably of the same origin as the Pc air-mass and therefore originally cold and dry. Its trajectory, however, lies over a warm, moist ocean-surface. By the time it reaches the Pacific Coast its lower layers, depending on the rapidity or slowness of its motion over the water, become extensively warmed and moist. The result is a steep lapse-rate and thermal instability. As the air-mass continues eastward it is further modified by the Rockies and the high plateaus which it must

Table 1--Variation of surface air-temperature (T_s) and of lapse-rate from 0 to 1915 meters over Boston and of specific humidity (q) at 1915 meters with air-masses during winter

Air-mass	T_s	Lapse-rate	q
		°C/100 m	
Pc	-7.4	0.22	1.5
Npc	0.8	0.19	2.5
Npp	2.3	0.26	2.3

Table 2--Variation of surface air-temperature (T_s) and of lapse-rate from 0 to 1915 meters over Boston and of specific humidity (q) at 1915 meters with air-masses during fall and spring

Air-mass	T_s	Lapse-rate	q
		°C/100 m	
Pc	2.3	0.40	2.1
Npc	10.2	0.43	2.1
Npp	8.1	0.35	3.1

traverse. Since the air is conditionally unstable it rises readily over the barrier losing in the process much of its moisture. The air at the same time becomes thoroughly mixed by convective and mechanical turbulence. As it comes down the east side it is considerably warmed. It fails, however, to displace the cold air at the surface, with the result that the air-mass is dry and relatively stable. As it reaches New England it is diminished somewhat in stability due to the warming of the lower layers as the air-mass moves eastward and also to the mixing effected by the Appalachians. Compared with the Pc- and Npc-types it is warmer and less stable in the lower layers.

Summer--In the summer the Pc air at the source, instead of being cooled from below by the extensive snow-cover, is heated in the lower layers. As it moves southward it becomes unstable and absorbs moisture; as the instability increases the moisture is rapidly carried upward and, unless the air-mass is considerably modified as in the central or southeastern portion of the United States, it arrives in New England still fairly cool and characteristically unstable. When it remains for some time in the central interior it becomes considerably warmer (Npc)--especially at the surface--but because of subsidence in the upper layers, not any more markedly unstable. Dealing as we do with early and late summer (spring and fall) conditions, we expect to find the typical summer characteristics of the Pc-Npc air-masses less pronounced. Accordingly we find still fairly low values of q, T_s, and lapse-rate (see Table 2). The Pp air-mass, though radically different in the summer at its source from the Pc air-mass, loses much of its stability by the time it arrives in New England and becomes warm in the lower layers. Still, as shown by Table 2, it is somewhat richer in moisture at approximately the 2-km level and still relatively stable.

The temperature-difference, ΔT_1

Cooling on a mountain top is produced by the expansion of air forced up from lower levels, as the air-mass sweeps over the barrier. The possibility of appreciable cooling by radiation is precluded, even with a calm, for the colder, heavier air is continuously replaced by adjoining warmer air at the same level [13].

Clearly a large amount of cooling on the summit is possible when air which is very stable and dry is forced up from the lowest level; in other words, with an air-mass having a small lapse-rate and small value of specific humidity, q, in the lowest layers. Unless this condition, of small decrease of temperature with elevation and low moisture-content, is fulfilled little cooling will be effected by air forced from below [14]. On the other hand, unless we do have a forced ascent of air, no cooling will result whatever the lapse-rate and q. The amount of cooling as expressed by the temperature-difference, ΔT_1, between the free air over Boston at 1915 meters and Mt. Washington is proportional to the lapse-rate of the free air, to the wind-velocity on Mt. Washington--which is an indication of the extent of the forced ascent--and, lastly, to the type of air-mass. (Because the air-mass type and season give a fair indication of moisture-content of the air-mass, the latter is not considered separately.) From the foregoing we shall expect ΔT_1 to be inversely proportional to the lapse-rate, to a lesser extent to the value of q, and directly proportional to the wind-velocity. This is shown in Table 3 (values in parentheses are based on few observations). The highest value of ΔT_1, 8°6, occurs in the winter with Pc air-masses (dry), which have a mean lapse-rate of 0°22 C/100 meters and a mean wind-velocity of 24.5 meters/sec. The slightly lower value of ΔT_1 for the Npc-type, 8°0, despite a smaller lapse-rate is due to a lower wind-velocity which indicates air forced up and over the summit from an intermediate level, and to a higher moisture-content of the air-mass. For the Npp type, the least stable of the three which has a mean velocity of 23.8 meters/sec, we have a temperature-difference of 7°0. In spring and fall, as the lapse-rate increases, ΔT_1 decreases. The lowest value of ΔT_1, 3°2, occurs in spring with Npc air-masses which have the highest mean lapse-rate 0°48 C, and a mean wind-velocity of 18.6 meters/sec, which is almost the lowest. With

Table 3--Variation of mean ΔT_1 (temperature free air over Boston at 1915 meters minus temperature on Mt. Washington), of wind-velocity on Mt. Washington, and of mean lapse-rate from 0 to 1915 meters over Boston for different seasons and air-masses

Air-mass	Fall			Winter			Spring		
	ΔT_1	Wind-vel.	Lapse-rate	ΔT_1	Wind-vel.	Lapse-rate	ΔT_1	Wind-vel.	Lapse-rate
	°C	m/s	°C/100 m	°C	m/s	°C/100 m	°C	m/s	°C/100 m
Pc	5.8	17.4	0.34	8.6	24.5	0.22	6.3	19.9	0.44
Npc	(5.0)	(21.3)	(0.27)	8.0	23.6	0.19	3.2	18.6	0.48
Npp	(7.2)	(23.8)	(0.30)	7.0	23.8	0.26	(5.4)	(24.0)	(0.39)

Table 4--Variation of ΔT_1 (temperature free air over Boston at 1915 meters minus temperature on Mt. Washington) with mean lapse-rate from 0 to 1915 meters over Boston for different seasons and air-masses

Air-mass	Lapse-rate in °C/100 m																	
	Fall				Winter				Spring				Fall, winter, spring					
	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00
	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
Pc	...	7.4	7.6	3.4	...	7.5	8.9	7.3	...	...	...	7.3	8.5	5.0	(0.3)	7.5	7.8	8.6	4.8	(0.03)
Npc	...	5.9	5.5	2.8	...	(9.0)	8.9	3.1	...	...	...	6.6	3.9	2.1	(1.8)	(9.0)	7.4	3.7	2.2	(1.8)
Npp	...	8.6	7.2	(3.7)	...	(12.2)	8.1	7.6	4.4	(-0.1)	...	(7.7)	5.2	4.3	...	(12.2)	8.2	6.7	4.2	(0.1)

one exception the values in parentheses, though based on few observations, show a similar consistency. Comparing fall and spring (Npp) values of ΔT_1, we find, while the wind-velocity is approximately the same, the higher value 7°2 occurs with the smaller lapse-rate, 0°30. The same appears in a comparison of results for Npp and Npc air-masses in the spring.

A readier picture of the trend of the temperature-difference relationship to lapse-rate and wind-velocity is obtained from Figure 1. Comparing fall, winter, and spring values of ΔT_1, for Pc, we find the highest value of ΔT_1 occurring with the smallest lapse-rate and highest wind-velocity. In spring (Pc) ΔT_1 is somewhat higher than in fall, but this, despite a steeper lapse-rate, is not surprising since the velocity in spring is considerably higher than in fall.

The decrease in temperature-difference with increase in lapse-rate is brought out more clearly (see Table 4) when ΔT_1 is classified according to lapse-rate group. However, here the wind-velocity factor is not taken into consideration and some discrepancies in the relationship should appear. These are especially noted in winter with Pc and, to a lesser degree, with Npc air-masses in the first two groups of lapse-rates namely, -0°40 to -0°11 and -0°10 to 0°20. A careful consideration reveals that these apparent discrepancies are quite natural. The great stability of these air-masses indicates an absence of strong winds and consequently no great upward movement of air. ΔT_1, instead of being larger for these two groups than for the following, might well have the same value or even smaller, depending on the wind-velocity.

Of special interest is the last group--lapse-rates of 0°81 to 1°00--where ΔT_1 is close to zero. These lapse-rates occurred with fairly moist air-masses, Npp in winter and Pc, Npc, in spring. Since the rate at which this upward forced element of air cools is, because of the latent heat of condensation, less than the observed lapse-rate, the summit should be a little warmer than the free air and ΔT_1 ought to be negative. This effect, however, is more than offset by the latitudinal temperature-gradient (see below).

Similarly, considering the influence of the wind-velocity on the temperature-difference we should expect to find in general large values of ΔT_1 with large wind-velocities. This is well shown in Table 5 for fall, winter, spring (Pc, Npc, Npp) combined. This trend of ΔT_1 should be more pronounced with stable air-masses, Pc, Npc (winter), and Npp (fall and spring), and less pronounced with unstable air-masses, Pc, Npc (fall and spring), and Npp (winter). ΔT_1 for Pc (winter) is seen to increase from 6°9 for the 6.1 to 12.0 meter-per-second velocity-group to 11°3 for the last group, more than 36.0 meters/sec. There are too few observations to show the relationship distinctly for the Npc type, yet on the whole ΔT_1 is greater for the larger velocity-groups here too. For Npp (fall) we get the large value of 8°1 with large wind-velocities. In spring, for the same air-mass type and the same velocity-group we get a

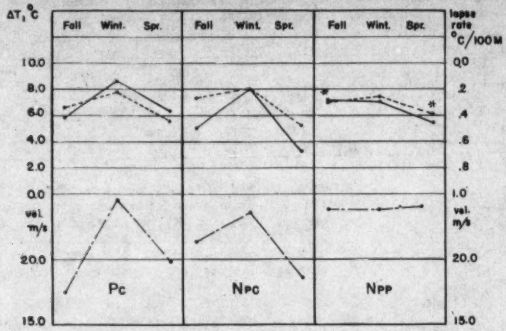


FIG 1 — Variation of mean temperature-difference, ΔT_1, between free-air over Boston at 1915 Meters and Mt. Washington, with mean lapse-rate, 0 to 1915 meters, over Boston, and wind-velocity on Mt. Washington

——— ΔT_1 temp.-difference —·—·— wind-velocity

- - - - - lapse-rate * indicates few cases

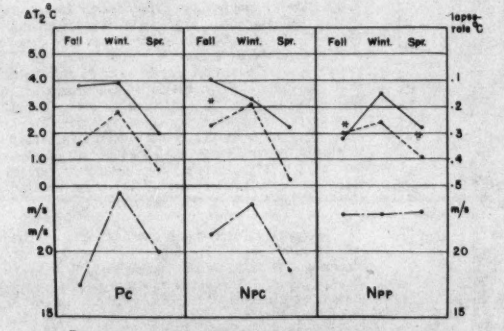


FIG 2—Variation of mean temperature-difference, ΔT_2, between the temperature which an element of air would have if raised from sea-level at Boston to 1915 meters and the observed temperature on Mt. Washington, with mean lapse-rate, 0 to 1915 meters, over Boston, and wind-velocity on Mt. Washington

——— ΔT_2 temp.-difference —·—·— wind-velocity

- - - - - - lapse-rate * indicates few cases

similar result (we also have lower values of ΔT_1 with decreasing velocities). For the second class of air-masses--the relatively unstable type--we find, because of the steeper lapse-rates, smaller values of ΔT_1 than in the case of the more stable class.

The fictitious temperature-difference, ΔT_2

We have seen that even when other factors are present, the forced ascent may be largely responsible for the lower temperatures of the Mountain. If this is true, the temperature on the summit must be the same as that of an element of air in the free atmosphere raised adiabatically (or condensation-adiabatically) from a lower level to the height of the summit. The temperature-

Table 5--Variation of ΔT_1 (temperature free air over Boston at 1915 meters minus temperature on Mt. Washington) with wind-velocity on Mt. Washington for different seasons and air-masses

Air-mass	Wind-velocity in meters per second						
	0.0 to 6.0	6.1 to 12.0	12.1 to 18.0	18.1 to 24.0	24.1 to 30.0	30.1 to 36.0	More than 36.0
	°C	°C	°C	°C	°C	°C	°C
				Fall			
Pc	4.8	(4.1)	4.4	6.3	8.7	6.7	...
Npc	...	...	4.0	...	(5.9)	(8.4)	...
Npp	...	...	...	...	...	8.1	...
				Winter			
Pc	...	6.9	7.2	6.2	9.5	10.4	11.3
Npc	...	...	6.6	8.0	(9.9)	(8.4)	...
Npp	...	...	(7.6)	(8.6)	6.9	...	...
				Spring			
Pc	4.9	5.4	6.8	6.7	6.1	8.3	(8.2)
Npc	2.9	1.4	3.7	4.1	4.0	4.2	...
Npp	...	...	...	(3.2)	(4.6)	8.2	...
				Fall, winter, and spring			
All 3	4.3	4.5	5.7	6.2	7.1	7.6	10.2

difference then is determined by the level from which the air reaching the summit rises. Several assumptions can be made as to the height of this level: The element of air may be brought up (1) from sea-level, (2) from the lowest level in the immediate vicinity of Mt. Washington, the base of the mountain, and (3) from some intermediate level between the summit and sea-level. Whether the air comes up from one level or another depends on a number of factors, such as the air-mass type, vertical temperature-distribution, wind-velocity, and extent of confining character of topography. The latter factor has a constant value and, in our case (vicinity of Mt. Washington), is very pronounced.

If the air on Mt. Washington is forced up from sea-level, then the difference in temperature between Mt. Washington and an element of air raised from the surface at Boston to 1915-meter height of Mt. Washington would be zero, provided the latitudinal temperature-gradient at that level were zero. The value of this quantity is not known but can be estimated in a general way. The average surface latitudinal temperature-gradient (based on maps of North America by C. F. Brooks and others, from Köppen-Geiger, Handbuch der Klimatologie) for the 132 miles between Mt. Washington and Boston, which was obtained from temperatures reduced to sea-level by adding 0°5 C per 100 meters of altitude, is roughly 2°3 C for our period of investigation.

This gradient is considerably greater than in the free air, especially in the winter when the ground in southern New England is frequently free of snow. Again, because it represents average conditions (fronts lying between the two stations on many occasions), it is greater than the surface-gradient which would correspond to our case.

The latitudinal temperature-gradient for the 2-km level in the free air as computed [15] for approximately the same latitude, but farther west (Drexel-Ellendale), is given as 0°73 C per degree of latitude. This would make about 1°5 for the distance between Mt. Washington and Boston. Since our conditions (same air-mass at both places) are of greater uniformity than those on which this value is based, it would be safe to assume that it is even less were it not for the relatively warm ocean to the south of New England. Assuming it to be approximately 1°5 C, we would expect to find then the average temperature-difference, ΔT_2, when the air on the summit is that brought up from sea-level and if we also neglect the specific humidity, roughly about 1°5. Conversely, when no air is forced up on the summit, the temperature-difference should be a maximum which in turn is a function of the lapse-rate and specific humidity. Hence the greater the stability and dryness of the air-mass and the shorter the ascent of air, the greater the value of ΔT_2. The value of this fictitious temperature-difference is then inversely proportional to the lapse-rate, the wind-velocity, and specific humidity (see note above).

In Table 6 is given the mean temperature-difference, mean wind-velocity, and lapse-rate for different seasons and air-masses. Barring the case of the Npp air-mass type (fall), the ΔT_2 value of which was based on few observations, we find the smallest values of ΔT_2 occurring with steepest lapse-rates (spring) and, conversely, with the highest values with most stable air-

Table 6--Variation of ΔT_2 (temperature on Mt. Washington minus temperature which element of air would have if raised from sea-level to 1915 meters), of wind-velocity on Mt. Washington, and of mean lapse-rate from 0 to 1915 meters over Boston for different seasons and air-masses

Air-mass	Fall			Winter			Spring		
	ΔT_2	Wind-vel.	Lapse-rate	ΔT_2	Wind-vel.	Lapse-rate	ΔT_2	Wind-vel.	Lapse-rate
	°C	m/s	°C/100 m	°C	m/s	°C/100 m	°C	m/s	°C/100 m
Pc	3.8	17.4	0.34	3.9	24.5	0.22	2.0	19.9	0.44
Npc	(4.0)	(21.3)	(0.27)	3.3	23.6	0.19	2.2	18.6	0.48
Npp	(1.8)	(23.8)	(0.30)	3.5	23.8	0.26	(2.2)	(24.0)	(0.39)

Table 7--Variation of ΔT_2 (temperature on Mt. Washington minus temperature of element of air at 1915 meters raised from from surface at Boston) with mean lapse-rate from 0 to 1915 meters over Boston for different seasons and air-masses

Air-mass	Lapse-rate in °C/100 m																	
	Fall				Winter				Spring				Fall, winter, spring					
	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00
	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
Pc	...	8.7	1.5	0.5	...	12.1	6.0	2.1	-1.2	...	...	6.0	1.8	0.5	(-0.8)	12.1	6.9	1.8	0.3	-0.8
Npc	...	7.8	1.6	-0.3	...	(10.5)	3.6	1.2	...	...	...	7.5	2.6	1.1	(-0.2)	(10.5)	5.9	1.8	0.9	(-0.2)
Npp	...	3.4	1.4	(2.6)	...	(8.4)	6.4	1.9	-1.0	(0.5)	...	(5.0)	3.1	1.5	...	(8.4)	5.4	2.1	-0.7	(0.5)

masses (winter). Comparing ΔT_2 for Pc and Npc (spring), we find the effect of the slightly greater stability, that is, lower lapse-rates, in the first case, to be of less influence on the value of ΔT_2 than that of the relatively higher vertical ascent of air. The same appears from a comparison of fall and winter values for Pc air-masses.

A consideration of the specific-humidity factor will help to explain some apparent discrepancies. It would appear, for example, since the wind-velocity and lapse-rate for Pc (winter) are respectively greater than for Npc, that ΔT_2 should be less for Pc. But this slight discrepancy may be explained by the higher moisture-content of the Npc air-mass type.

No account has yet been taken of the latitudinal temperature-gradient. Since this quantity varies little with season at the 2-km level, we can add approximately 1°5 to all the values of ΔT_2. This would make all the values in Table 6 higher. On the other hand, had they all been zero, it would then indicate that Mt. Washington experiences in every case a maximum amount of possible cooling. The conclusion may now be drawn that, on the average, in spring and perhaps in fall and with Npp air-masses, the summit experiences a greater proportion of the maximum possible cooling than in the other seasons and with other air-masses.

Classifying the temperature-difference with lapse-rate group the variation of ΔT_2 is seen more definitely (see Table 7). Of special interest are the high values of ΔT_2 in the first and, to a lesser degree, in the second groups. The lapse-rates in these groups denote very stable air-masses and hence an absence of strong winds. Since ΔT_2 is inversely proportional to the wind-velocity, the large values of ΔT_2 for these groups are quite normal. The sharp drop in ΔT_2 between the second and third group is in accord with the principle of abrupt increase in wind-velocity with the establishment of instability. Once instability is set up the increase in wind-velocity is more gradual and consequently the decrease in the value of ΔT_2 in the other groups is less too. The trend of the relationship of ΔT_2 to the lapse-rate in Table 7 is just the reverse of ΔT_1 in Table 4, previously considered. Since ΔT_1 is directly proportional to the wind-velocity, there was but a small decrease (at times none or even an increase) between the second and third groups, but there were sharp drops in ΔT_2 between the others.

In examining the variation of the fictitious temperature with wind-velocity separately (see Table 8) we note how ΔT_2, with one exception, decreases for the average case (all seasons and air-masses combined) with increasing wind-velocity. Barring the figures in parentheses this trend is also apparent for the individual types and seasons. Considering that the lapse-rate is not taken into account, we find that the relationship between ΔT_2 and wind-velocity is brought out quite satisfactorily. We might point out here the relationship of wind-velocity to lapse-rate.

Table 8--Variation of ΔT_2 (temperature on Mt. Washington minus temperature of element of air at 1915 meters over Boston)with wind-velocity on Mt. Washington for different seasons and air-masses

Air-mass	Wind-velocity in meters per second						
	0.0 to 6.0	6.1 to 12.0	12.1 to 18.0	18.1 to 24.0	24.1 to 30.0	30.1 to 36.0	More than 36.0
	°C	°C	°C	°C	°C	°C	°C
				Fall			
Pc	8.5	(10.6)	5.2	1.6	1.7	-1.4	...
Npc	...	...	3.9	...	(3.3)	(5.7)	...
Npp	...	...	...	...	...	3.4	...
				Winter			
Pc	...	8.9	6.2	2.6	3.2	0.5	-0.1
Npc	...	...	4.4	1.7	(5.9)	(2.4)	...
Npp	...	...	(8.2)	(6.0)	1.9	...	...
				Spring			
Pc	4.1	5.4	3.4	1.8	1.0	-1.4	(1.8)
Npc	7.6	3.2	2.2	-0.5	3.3	2.1	...
Npp	...	...	...	(4.2)	(1.8)	2.2	...
				Fall, winter, and spring			
All 3	6.8	5.6	4.2	1.7	2.4	1.5	0.6

Table 9--Variation of mean lapse-rate with ΔT_1 groups for different seasons and air-masses

Air-mass	ΔT_1 in °C				
	Less than 0.0	0.0 to 3.0	3.1 to 6.0	6.1 to 9.0	More than 9.0
	°C/100 m	°C/100 m	°C/100 m	°C/100 m	°C/100 m
			Fall		
Pc	....	0.52	0.37	0.23	0.25
Npc	....	0.45	0.27	0.24	(0.11)
Npp	....	....	0.41	0.23	(0.20)
			Winter		
Pc	....	....	0.23	0.16	0.28
Npc	....	....	0.31	0.18	0.14
Npp	(0.94)	(0.80)	0.36	0.14	0.07
			Spring		
Pc	(0.82)	0.73	0.50	0.38	0.31
Npc	0.61	0.60	0.45	0.22	(0.46)
Npp	....	(0.55)	0.42	(0.28)	(0.14)
			Fall, winter, and spring		
Pc	(0.82)	0.59	0.39	0.25	0.28
Npc	0.61	0.57	0.37	0.22	0.20
Npp	(0.94)	0.68	0.40	0.19	0.12

An approximation of the true temperature-difference

We have seen from above how the temperature-difference, ΔT_1, between the free air at 1915 meters and Mt. Washington varied with the mean lapse-rate, wind-velocity, air-mass, and season. It was also shown how this temperature-difference, by taking cognizance of the latitudinal temperature-gradient in the free air, could be explained on the basis of a forced ascent of air from sea-level at Boston. In the classification employed above, ΔT_1, as well as the fictitious temperature-difference ΔT_2, appeared, among others, as a function of lapse-rate and wind-velocity which in turn were divided, for want of extensive observational material, into several arbitrary groups thus making the values of ΔT_1 and ΔT_2 approximate. While the degree of approximation is not known we can, instead of estimating it, attempt to determine it by trial. For this purpose we shall divide the temperature-differences into several groups and tabulate the lapse-rates and

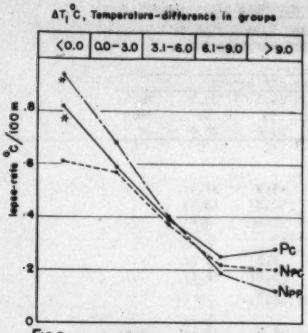


FIG. 3—Variation of ΔT_1, temperature-difference free air over Boston at 1915 meters minus Mt. Washington, with mean lapse-rate, for different air-masses

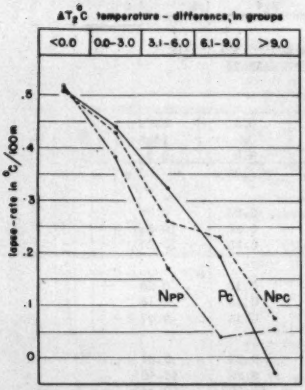


FIG. 4 Variation of ΔT_2, temperature-difference, element of air at 1915m raised from the surface at Boston minus temperature on Mt. Washington, with mean lapse-rate, for different air-masses

wind-velocities for each of them. In doing so we shall also have an opportunity to see how close the relationship established before holds, and incidentally to verify it.

It was already seen from Tables 4 and 7 that the temperature-difference ΔT_1 and ΔT_2 sometimes assumed a small negative value when Mt. Washington was warmer than the free air over Boston at the same level. This occurred with air-masses having a steep lapse-rate and a high moisture-content. It was shown that the small magnitude of this negative value was due to the effect of the latitudinal temperature-gradient. We should, therefore, in grouping the temperature-differences, have a group with negative values, that is, ΔT is less than 0.

Considering now Table 9 in detail we see that in winter negative temperature-differences occurred with higher lapse-rates than in the spring. This is in part due to the greater amount of latent heat of condensation available with the relatively moister air-masses in spring and fall. Further, in following the trend of lapse-rate change with ΔT_1 we find that with few exceptions the lapse-rate decreases with increasing temperature-differences. This was also found in Table 4. The explanation for these exceptions, as well as for the sharp decrease in lapse-rate between the low-value groups and the smaller decrease or even an increase between the two high-value groups, is the same as for the similar trend in the variation of the temperature-difference with lapse-rate as found in Table 4, and was given earlier. The effect of the wind-velocity is shown by the progressive decrease in lapse-rate. This is indicated in Figure 3, which is based on values of ΔT_1 tabulated for the three seasons jointly (see also bottom of Table 9). The increase in lapse-rate for Pc air-masses between the fourth and last group is to be ascribed to higher wind-velocities associated with most of these cases.

The influence of the wind on the temperature-difference gives a similar relationship, showing the velocity to increase with increasing values of ΔT_1 (see bottom of Table 10). Some inconsistencies appear when an examination of the relationship for the individual types and seasons is made. For the most part they can be explained in the light of what has been said above, namely, the effect of varying lapse-rates associated with each value of velocity.

It remains now to separate the two effects and to tabulate ΔT_1 as a function of lapse-rate as well as of wind-velocity. (Unfortunately there are too few data to allow a further subdivision, that is, for air-masses and seasons). However, before proceeding with a discussion of the results of such a tabulation it is worth while to show again that the temperature-difference, in the manner classified above, is, barring the latitudinal temperature-gradient, the result of dynamic cooling. This will be done by employing the method used before, showing the variation of lapse-rate and then wind-velocity with various values of ΔT_2, a fictitious temperature-difference.

Recalling that ΔT_2 is inversely proportional to the lapse-rate we find, from a consideration of the results for fall, winter, spring seasons combined (see Table 11), that on the whole this is true for the individual air-masses as well (see also Fig. 4).

Examining the trend of the relationship for each season separately we see that the lapse-rate, while generally decreasing with increasing ΔT_2, in some instances--notably in winter--

Table 10--Variation of wind-velocity on Mt. Washington with ΔT_1 groups for different seasons and air-masses

Air-mass	ΔT_1 in °C				
	Less than 0.0	0.0 to 3.0	3.1 to 6.0	6.1 to 9.0	More than 9.0
	m/s	m/s	m/s	m/s	m/s
			Fall		
Pc	....	15.9	15.7	16.1	22.5
Npc	....	19.0	21.5	19.3	(34.1)
Npp	....	....	20.7	23.3	(30.5)
			Winter		
Pc	....	....	21.3	20.9	28.8
Npc	....	....	20.8	25.5	22.6
Npp	(22.7)	(23.4)	20.9	(32.4)	(35.0)
			Spring		
Pc	(10.0)	(21.1)	14.3	20.4	27.5
Npc	9.1	16.1	20.2	26.4	(25.3)
Npp	....	(10.9)	23.6	(33.2)	(34.1)
			Fall, winter, and spring		
All 3	13.1	17.8	18.8	25.6	26.8

Table 11--Variation of mean lapse-rate with ΔT_2 groups for different seasons and air-masses

Air-mass	ΔT_2 in °C				
	Less than 0.0	0.0 to 3.0	3.1 to 6.0	6.1 to 9.0	More than 9.0
	°C/100 m	°C/100 m	°C/100 m	°C/100 m	°C/100 m
			Fall		
Pc	0.53	0.36	0.36	0.20	0.06
Npc	0.47	0.48	(0.17)	0.15	0.01
Npp	(0.35)	0.33	0.24	....	....
			Winter		
Pc	0.38	0.27	0.28	0.16	-0.14
Npc	(0.22)	0.28	0.15	0.12	(-0.13)
Npp	0.58	0.41	0.13	0.03	(-0.34)
			Spring		
Pc	0.58	0.50	0.34	0.26	(0.13)
Npc	0.61	0.59	0.33	0.36	(0.24)
Npp	(0.56)	0.38	....	(0.08)	....
			Fall, winter, and spring		
Pc	0.51	0.44	0.32	0.19	-0.03
Npc	0.51	0.43	0.26	0.23	0.07
Npp	0.52	0.38	0.17	0.04	0.06

decreases rapidly between the two groups of higher values of ΔT_2 and, on the whole, but little in the lower values of ΔT_2 groups. This is due to the small wind-velocities which occur with very stable air-masses. Comparing Table 11 with Table 7, we recall that in the latter we have found high values of temperature-difference with low lapse-rate groups, also sharp decreases in ΔT_2 between the high lapse-rate groups. Accordingly we should find in Table 11 low values of lapse-rate with high values of ΔT_2 and a sharp decrease in lapse-rate between the high-value groups of ΔT_2. Such is the case.

Since ΔT_2 is also inversely proportional to the wind-velocity (see Table 12) we find the velocity decreasing with increasing temperature-differences (ΔT_2). Where the average case is treated, as shown at the bottom of Table 12, the decrease in velocity with increasing values of ΔT_2 is pronounced, the average velocity in the highest group being less than half the value of that in the lowest. To get the various shades of the relationship as well as to explain the ap-

Table 12--Variation of wind-velocity on Mt. Washington with ΔT_2 groups for different seasons and air-masses

Air-mass	ΔT_2 in °C				
	Less than 0.0	0.0 to 3.0	3.1 to 6.0	6.1 to 9.0	More than 9.0
	m/s	m/s	m/s	m/s	m/s
			Fall		
Pc	26.3	17.4	14.2	14.8	5.5
Npc	24.2	19.5	(17.3)	25.4	18.2
Npp	(18.5)	27.5	22.7	....	....
			Winter		
Pc	35.0	22.0	26.8	18.5	11.2
Npc	(19.4)	27.6	18.0	(24.4)	(24.6)
Npp	27.5	25.8	20.9	22.4	(17.9)
			Spring		
Pc	23.5	21.8	14.3	16.5	(7.3)
Npc	20.6	24.9	16.3	9.8	(13.3)
Npp	(16.9)	27.3	....	(25.4)	(22.7)
			Fall, winter, and spring		
All 3	24.4	23.9	19.0	18.4	11.7

parent discrepancies, we must introduce the lapse-rate factor and the other characteristics of the air-mass. However, this has been done already (see above) and need not be repeated here. Instead, we can compare the results of Table 12 with those in Table 8, where a similar relationship is given. There the classification is reversed and we shall have to compare the temperature-trend with the velocity-trend. We find that large amplitudes in wind-velocity (20.8 and 23.8 meters/sec) occur with Pc air-masses in fall and winter (see Table 12). From Table 8 we get the large amplitudes in ΔT_2, 9°9 and 9°0 C, for the corresponding seasons and air-masses. Unfortunately there is no complete series available for the other cases for a similar comparison.

The last two tables have further served to confirm our assumption that the coldness of the summit was due to a forced ascent of air. However, we still have another way of checking this assumption.

A limited number of observations from the Base Station of Mt. Washington allows us to compute the difference between the temperature which an element of air would have if raised from that level (790 meters) to 1915 meters and the temperature observed on Mt. Washington. This fictitious temperature-difference, ΔT_3, should correspond to the fictitious temperature-difference ΔT_2 computed from observations at Boston, provided the latitudinal temperature-gradient in the free air is taken into account. A comparison of the two was made by adding first 1°5, the approximate latitudinal gradient, to ΔT_2. The results are 3°5 for ΔT_2 and 2°8 for ΔT_3 (ΔT_3 is smaller than ΔT_2, as we should expect, for ΔT_2 is derived from adiabatic reduction through a greater vertical distance).

We can now return to the question of the actual temperature-difference. By grouping the lapse-rates according to temperature-difference and velocity-groups (see Table 13) we separate the factors affecting the temperature-difference most, namely, the wind and mean vertical temperature-distribution. Since ΔT_1 is inversely proportional to the lapse-rate we should find increasing values of lapse-rate with decreasing values of ΔT_1 for each velocity-group and, since the temperature-difference is also directly proportional to the velocity, we must get an increasing lapse-rate for each ΔT_1-group from one velocity-group to another. This is on the whole shown by Table 13 (see also Fig. 5). A closer examination reveals a disproportionately small increase (or none) in lapse-rate as we go from the first temperature-difference group (ΔT_1 greater than 9°0) to the next (ΔT_1 from 6°1 to 9°0) and also an equally slight increase (or none) in lapse-rate in some instances from one velocity-group to another.

The first discrepancy may be explained as follows. In considering the temperature-difference we can bear in mind the fact that more cases of ΔT_1 in the higher group have occurred in the winter than during the other seasons. We can then conclude that since there is a smaller amount of heat of condensation available with the air-masses in winter than in the spring or fall, the same lapse-rate--everything else being equal--will be responsible for a higher temperature-difference in winter. The discrepancy would, in all probability, have disappeared had there been

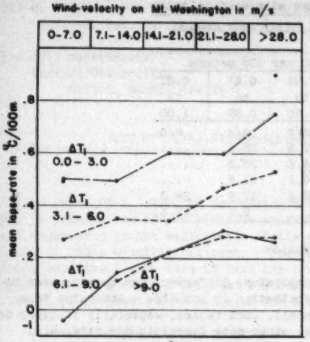


FIG. 5- Variation of ΔT_1 °C, temperature-difference in groups with lapse-rate, for different wind-velocity groups

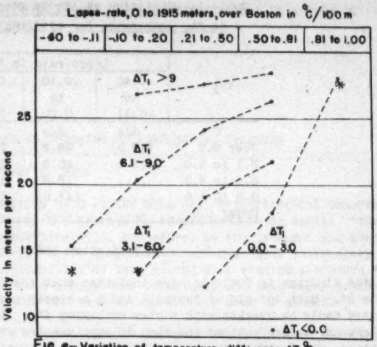


FIG. 6- Variation of temperature-difference, ΔT_1 °C, in groups, with wind-velocity on Mt. Washington in meters per second for different lapse-rate groups

Table 13--Variation of ΔT_1 in groups with lapse-rate over Boston for different wind-velocity groups

ΔT_1	Wind-velocity in meters per second				
	0.0 to 7.0	7.1 to 14.0	14.1 to 21.0	21.1 to 28.0	More than 28.0
°C	°C/100 m	°C/100 m	°C/100 m	°C/100 m	°C/100 m
Over 9.0	....	0.11	0.22	0.28	0.27
6.1 to 9.0	-0.04	0.14	0.22	0.31	0.26
3.1 to 6.0	0.27	0.35	0.34	0.47	0.53
0.0 to 3.0	0.50	0.49	0.60	0.59	0.75
Under 0.0	0.58	....	....	....	0.90

at hand more extensive observational material, for this would have allowed a subdivision of ΔT_1 with regard to specific humidity. More observations would also enable us to shorten the range in the velocity and temperature-difference groups, which might eliminate other discrepancies and make the relationship in general more consistent.

Table 11 has shown how the temperature-difference can be identified with a certain group provided the lapse-rate is given and provided a general estimate of the wind-velocity can be made. In practice, however, we can measure the wind-velocity but can only estimate the lapse-rate in a general way from temperatures of Base Station versus summit, or even Boston versus the summit of Mt. Washington. We shall therefore classify the temperature-difference groups with wind-velocity and lapse-rate groups.

As expected, Table 14--barring the values in parentheses--shows for each lapse-rate group a downward trend of wind-velocity with decreasing ΔT_1 group and an upward trend with increasing lapse-rate group (see also Fig. 6). In other words, given the same lapse-rate, a shorter ascent of air (as indicated by smaller velocities) will produce less cooling on the Mountain and, consequently, give smaller values of ΔT_1. On the other hand, a higher ascent of air will be required to produce the same value of ΔT_1 when the lapse-rate becomes steeper. Also note, as a consequence, that with lapse-rates of -0°40 to -0°11 no values of ΔT_1 smaller than 6°0 occurred and, in the group 0°81 to 1°00, no values of ΔT_1 greater than 3°0 were found. Again in the last group, ΔT_1 less than 0°0, we find negative temperature-differences occurring only with steep lapse-rates.

Table 14--Variation of ΔT_1 in groups with wind-velocity on Mt. Washington for different lapse-rate groups

ΔT_1	Lapse-rate in °C per 100 meters				
	-0.40 to -0.11	-0.10 to 0.20	0.21 to 0.50	0.51 to 0.80	0.81 to 1.00
°C	m/s	m/s	m/s	m/s	m/s
Over 9.0	(13.5)	26.8	27.5	28.4	....
6.1 to 9.0	15.4	20.3	24.2	26.3	....
3.1 to 6.0	....	13.3	19.1	21.8	....
0.0 to 3.0	....	(13.5)	12.4	17.9	28.0
Under 0.0	....	....	....	9.1	(27.5)

Application and conclusion

The findings in Table 14 have indicated that the temperature-difference can be estimated to within 3°. With the aid of Tables 4 and 5 a closer approximation is possible. Any value thus obtained could be checked with tables employing ΔT_2. In all, such tables, especially if based on more extensive observations and also if supplemented with other data (specific humidity, wind-direction, etc.), would enable one to obtain an approximate temperature in the free-air at the level of the summit. However, in addition to this there is available other information which, when used in conjunction with these tables, would greatly enhance the accuracy of the results. An analysis of the synoptic situation, for example, would give a picture of the characteristics of the air-mass in question. Of significance would be observations from Mt. Washington of the heights of inversions or sheet-clouds present. In order of importance the information required is: (1) Air-mass (and season); (2) wind-velocity (also direction) on Mt. Washington; (3) temperature and specific humidity on Mt. Washington, at base-stations, and at Boston; (4) synoptic analysis; (5) other observations.

Using this information, the temperature in the free air at 1915 meters has been computed for a number of cases with encouraging results. Of these, 67 per cent gave temperatures which came to within half a degree of the observed temperature, 22 per cent within one degree, and the rest within 1°5.

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USE OF ULTRA-HIGH FREQUENCIES IN TRACKING METEOROLOGICAL BALLOONS

Arthur E. Bent

On February 1, 1935, in addressing a meeting held at the Blue Hill Meteorological Observatory in celebration of its fiftieth anniversary, Dr. Charles F. Brooks used these words: "The next major step in the exploration of the atmosphere will, therefore, be the frequent and general use of radio sounding-balloons, a relatively recent invention..... Blue Hill Observatory should experiment with them to test the practicability of this method as a routine procedure." In the following month a program of study of this problem was undertaken and this paper presents a report of progress, an outline of the problem, and suggestions for the mode of attack.

A survey of the problem in general and a history of previous activities in radio sounding have been presented in a paper by Lt. William H. Wenstrom [1], and readers are referred to that source. The most severe problem is undoubtedly the rigorous limitation of weight. Much progress has been made in this direction and there appears a possibility of some further slight refinement. The meteorograph and radio equipment must prove effective within certain limitations. The meteorograph must be accurate within the range to be covered and the radio equipment must provide an adequate signal for recording and for direction-finding. Severe conditions of temperature and moisture will be found in spite of which the equipment must continue to function.

Perhaps the first problem to be faced is the choice of wave-length. Previous work has been confined to the use of what are now considered the longer radio waves, namely, from 20 to 150 meters. Radio energy on these waves is easy to generate but, due to the amount of wire and other equipment required, the complete apparatus cannot compete in weight with the ultra-short waves. The receiving equipment on the longer waves has been developed to a high order of effectiveness but is elaborate and expensive. Direction-finding on the longer waves is effective but recent developments in the ultra-short-wave field hold promise in this direction. At the Blue Hill Observatory our experience with the ultra-short waves, which we have been using to provide communication with the Observatory on Mt. Washington (New Hampshire) 142 miles away, has led us to favor the further use of these frequencies in meteorological work [2]. One of the outstanding characteristics of the short waves is their ability to cover great distances with very low power when physical interference does not intervene between receiving and transmitting point--a condition which would be likely to exist in radio-sounding work. Freedom from static interference is another advantage of the very short waves, where a flash of lightning only a short distance away produces only a slight click. Static might impose a very definite limitation on the effectiveness of longer waves for use in summer and in certain latitudes. Interference from signals being used in communication is also a problem on the longer waves, while the possibility of interference with other services by the signal from the sounding balloon when used in congested areas is a serious matter. Interference from other signals is not absent on the ultra-short waves but the situation in that respect is much more favorable than on the longer waves. Comparative absence of fading and similar propagation-characteristics also favors the short waves. General simplicity of the equipment for both sending and receiving and compact antennas for these frequencies are added advantages.

These considerations led to the conclusion that experimenting with the ultra-short radio waves for use in radio sounding was justified. Following familiar technique short radio waves may be generated easily within the range of from seven to about two meters. When waves shorter than two meters are desired, special methods must be employed which do not appear at present to lend themselves readily to radiometeorography. Waves in the centimeter-range are tempting from the point of view of the simplicity and small size of direction-finding antennas, but the power required to operate the vacuum-tube now available for use at this frequency is greater than that required for those to generate waves of five meters. It is quite possible that advances in vacuum-tube design may result in suitable tubes for the centimeter waves and it would appear that in general we should adapt the shortest waves possible to our needs in sounding work. At present, however, it will probably be most profitable to confine our study of ultra-high radio frequencies for sounding balloons to the region about five meters.

More specifically, the problem divides itself logically into certain parts and we will

treat more in detail of the balloon, the meteorograph, the radio sending, and the radio receiving and recording.

The balloon--The weight of the radio equipment and the meteorograph is of the order of a kilogram. The lifting power of the balloon must be enough in excess to give a rapid rate of ascent, both so that the distance between radio transmitter and receiver does not become too great, and also to provide a more useful meteorological record. The balloon must be designed so that the required lifting power is secured with a minimum of air-resistance.

The required lifting power can probably be secured more cheaply by means of several small balloons rather than one large one. Several balloons might be arranged in a vertical line to minimize air-resistance. Rubber balloons, inflated with hydrogen, will provide the lifting power economically. It will be necessary to provide a parachute for the equipment to avoid injury to the public, and a notice of reward offered for the return of the instruments should be attached.

The meteorograph--The meteorograph operates on a modification of the Olland telemeteorograph principle devised by Dr. K. O. Lange of the Massachusetts Institute of Technology and associated with the Observatory in the development of the radio sounding equipment, who will describe the instrument more in detail. A contact-arm, rotated by a clock-mechanism, makes one revolution per minute about a circular clock-like face in synchronism with the rotation of the recording chronograph. This arm is equipped with a light spring for making an electrical contact. Once in every revolution a timing contact is made. The arm of each meteorological indicating unit is arranged to describe an arc over a portion of this circular face. The spring-contact will complete the electrical circuit upon passing over each indicating arm as it makes its journey about the circle. As a continuous tone is desired from the radio the contact will be used to cause it to cease to transmit for a moment. The watch-movement used to rotate the contact-arm must be fitted with an invar balance-wheel to compensate for temperature-changes, and the whole radio unit must be protected from moisture by a cone.

Radio sending--In radio sounding a first consideration is the choice of vacuum-tube to be used. While there is a great variety of tubes made for use in radio receivers, there are few types suitable for our purpose. The limiting factor will usually be the power required to operate the filament of the tube. Tubes designed to operate with a filament-voltage of two and a half or six volts in all cases require too much current to be supplied from a light-weight battery. This is the great disadvantage of the new RCA 955, which will generate such high frequencies readily. This tube is justly called the acorn tube and its weight is only 4.7 grams. The filament-power, however, seems excessive for our work. Radio engineers could no doubt design a tube to operate on 4-1/2 volts, with a low filament-current consumption, which would be an effective generator of radio frequencies up to, say, 240 megacycles, or 1-1/4 meters. The type-30 tube, however, fills our requirements well at a wave of five meters. This tube operates on a voltage of two and a current of 60 milliamperes, and is suitable for operation by small batteries. As it comes from the manufacturer it weighs 32 grams. The bakelite base with four metal prongs which fit into the tube-socket may be removed, after which the weight is 23 grams. When the light radio-frequency circuit is attached for operation on a wave of 2-1/2 meters the weight becomes 32 grams, while a circuit for generation of 5-meter waves brings the weight to 38 grams. These weights compare very favorably with those where the wave is of the order of 150 meters, and the power-supply requirements are substantially the same.

Almost any of the conventional oscillator-circuits will function readily at this frequency. Due to the very short waves all circuit-constants are much reduced in size--a favorable circumstance when attempting to save weight. When using a single tube as oscillator the grid-coil may be half an inch in diameter and consist of five turns, the plate-coil being of similar dimensions. It is desirable to use a rather large, rigid wire such as No. 16 to make the coils self-supporting. If two tubes are used the filaments may be connected in series, and as a 4-1/2 volt battery will be used for filament-supply, this will not result in any greater power-consumption from the battery, for when using a single tube a resistance must be used to drop the voltage to the desired value. The two-tube transmitter weighs about twice as much as the single tube and is physically not as sturdy, although the radio energy available is clearly greater.

The most promising power-supply for the tube-plate circuit is the buzzer-transformer, as used by Lt. Col. W. R. Blair [3]. This is an efficient form of the familiar spark-coil. The buzzer-interruptions provide a tone-modulated signal, which is desirable on ultra-short waves. In our experiments we have wound transformers by hand weighing from 62 to 250 grams, the interruptions in the primary circuit being provided by a separate buzzer. It is indicated that this part of the equipment should be a commercial product. Quantity production will be necessary to keep the cost of this part at a reasonable figure. The transformer draws from 50 to 150 milli-

amperes from the battery of 4-1/2 to 9 volts, depending upon the adjustment of the buzzer. The problem here is to secure a buzzer which will not stick in operation. With proper construction this will probably not prove a serious difficulty. A weight of about 200 grams may be expected for this part of the equipment.

The battery for operation of the transmitter may be a small 4-1/2 volt "C" battery such as the Burgess No. 5360. This battery weighs 150 grams and in similar use has given three or four hours' service. The weight of the battery cannot be reduced without impairing its capacity to provide current, but the possibility of refinement in this direction is indicated. For use to heights of the order of 20,000 feet this battery is quite adequate, but at greater heights the low temperatures encountered become a problem. In this connection the use of some thermal insulation is suggested as well as the introduction of a heat-generating compound. Generation of heat, however, must be done with caution because of the possibility of affecting the temperature-record.

The radio antenna for use at five meters is a phosphor-bronze wire 2.5 meters long, No. 24 gage. The radio and meteorograph may well be suspended from the balloon by the antenna.

An experimental assembly adjusted to 2-1/2 meters was sent up in a plane and the signal was received about 50 miles away. The level of the signal, however, even at near-by points was not satisfactory. The radio-frequency energy available in a given circuit begins to drop off rapidly below five meters, and, while the use of such a wave has not been discarded, our work has been carried on with the five-meter wave. Using a pair of type-30 tubes in a push-pull circuit, with a power-supply as described, good signals were received from a plane, and signals were heard at about 50 miles. The lightest complete radio unit assembled weighed 591 grams, but many further economies in weight are still possible.

Radio receiving and recording--Reception on the ultra-short waves is accomplished with super-regenerative circuits. When effectively constructed these receivers are nearly, if not actually, as sensitive as the much more elaborate superheterodyne and have the great advantage of a rather broad tuning-characteristic. This is important since the simple oscillators used in this work are not sufficiently stable to permit reception on a superheterodyne. The receiver must be designed for a dual function, namely, to provide a signal to operate the recording equipment and to provide a signal for direction-finding purposes.

In designing the receiver for recording a difficulty is met with in the high noise-level characteristic of superregenerative receivers. This noise is made up of components over a rather wide audio-frequency range. When reception of speech is desired the noise can only be slightly reduced without impairing the quality of the voice, but when interested in only such a tone as emitted by one of the radio sounding transmitters a great deal can be accomplished by way of filtering out this disturbance. The recording receiver now in use is equipped with a low-pass filter which removes all frequencies above 1000 cycles per second, leaving the receiver relatively quiet but not interfering with receptions of the tone-signal. A sensitive relay-device is operated by the change in plate-current of a heavily biased amplifier-tube. This receiver has been used to record a tone sent to Blue Hill from Mt. Washington, and controlled by the anemometer-contact at the latter point. Indication is that a moderate signal will be adequate to operate the recording apparatus. A reference is given in note [4] to the design of simple super-regenerative receivers.

Two superregenerative receivers close together interfere badly with each other so that direction-finding must be done on the same instrument. This is accomplished by inserting a connection for listening in the circuit and picking up the signal originally on a directive antenna. There must thus be a continuous signal from the balloon, to be broken up by intervals to transmit the meteorological record. Unless equipment can be designed to give a vertical angle bearing, the location of the balloon must be secured by observations with two direction-finding stations. Our preliminary experiments with horizontal doublet antennas indicate that an adequate bearing can be secured, but it may prove desirable to construct more elaborate directive arrays. A paper by Southworth treats exhaustively of directive antennas [5]. Simple directive antennas for use at five meters are discussed by R. A. Hull [6]. The physical dimensions of these antennas are within limits which make their construction for rotation possible.

The records are taken at Blue Hill on a chronograph which is intended to be synchronized with the rotation of the contact on the meteorograph. The drum of the chronograph is arranged for rotation in a period of one minute. As the drum makes one rotation the recording pen-mechanism is lowered so that successive lines are separated by about two mm, giving room on this instrument for a record of about two hours. As the relay on the recording receiver closes, a circuit is made to the pen-magnet causing it to make a mark on the paper. The timing pulse from

the balloon should come at the same point on the chronograph-drum, but two mm lower at each revolution, giving a straight vertical line if the meteorograph and chronograph were properly synchronized. The record of pressure, temperature, and humidity should give a curve of satisfactorily open scale, since the chronograph-drum has a circumference of 120 cm.

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THE RADIO-METEOROGRAPH PROJECT OF BLUE HILL OBSERVATORY, HARVARD UNIVERSITY--A PRELIMINARY REPORT

K. O. Lange

Meteorological observations of the upper air have attained rapidly growing significance to all phases of the meteorological science. Their recent successful application in preparing the daily weather-forecast has given them a considerable practical importance in excess of their mere scientific values. In the United States alone, the number of stations which take measurements regularly of pressure, temperature, and humidity up to 17,000 feet was recently increased to twenty. These stations are operated in addition to the stations which measure the wind-direction and wind-velocity aloft. Besides these routine observations, the United States Weather Bureau and private institutes conduct special investigations into the highest layers of the atmosphere in order to find further correlations between upper-air phenomena and weather-developments.

Ascensions by airplane now have taken the place of all other methods of exploring the upper air, as far as regular soundings to 20,000 feet are concerned. Sounding balloons have retained their traditional position as the most efficient means of exploring the highest layers of the atmosphere. Pilot-balloon runs have remained as the only practicable way of determining the wind at high levels.

Notwithstanding all their merits, these methods have their decided disadvantages. Aerological airplane-ascents are very expensive as compared with surface weather-observations. This is the reason why at present the synoptic meteorologist has to get along with a much smaller number of daily flights than is desirable and necessary. Moreover, airplane-ascents can not be carried out under certain unfavorable weather-conditions, or, at least, they then imply the risk of life. It is in such weather-situations, however, that aerological soundings are most needed.

The outstanding disadvantage of the sounding-balloon method is that the meteorographs, which are carried up by the balloon, frequently are not recovered until weeks after the ascension, if they can be found at all. Thus, balloon-soundings can not be utilized in the daily weather-forecast. Chances are small to obtain results of measurements with sounding balloons in isolated regions and over the sea.

Pilot-balloon observations by means of theodolite sightings are only possible as long as the balloon is visible from the ground. Thus, no high wind-measurements are obtained on days when the ceiling is low. This means that in bad weather not only the aerological ascents but also high wind-observations can not be counted on.

It should be pointed out here that meteorology is not the only science vitally interested in upper-air data and that synoptic meteorology is not the only field that makes immediate practical use of these data. Ballisticians need upper-air data for the computation of ballistic densities and the military importance of quick and reliable information on the upper-air condi-

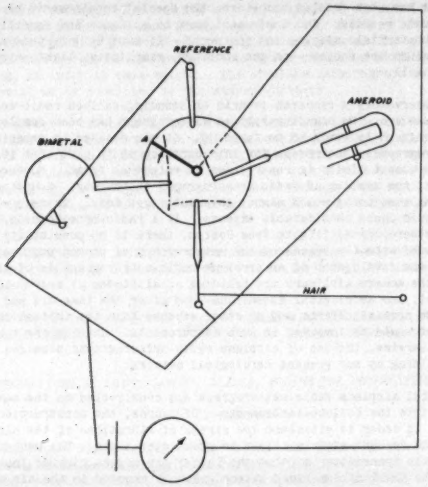

FIG. 1—SCHEMATIC DIAGRAM SHOWING PRINCIPLE OF RADIO-METEOROGRAPH

tions may even exceed the importance of these data to the meteorologist. At present there is practically no possibility of securing such information quickly and conveniently.

Already many years ago it was realized that more regular and more reliable results of upper-air observations may be obtained by using a small radio sender in connection with a sounding balloon, which would permit reception of the various data at the ground while the balloon is ascending. Many attempts have been made in all parts of the world toward the solution of this problem. Some of the European instruments of this kind have been used successfully for aerological observations in polar regions. But while opinions differ as to their reliability and accuracy, there can be no doubt that their weight and price make them prohibitive for general usage.

When the Blue Hill Observatory--following its tradition as one of the oldest and foremost aerological institutions--decided on a research program on this most up-to-date aerological method, it well realized that the development should finally lead to a radio-meteorograph of such a degree of foolproofness, accuracy, and low price that it has a chance to take the place of other methods favored so far.

In the foregoing paper, Arthur E. Bent gave a brief outline of the problems of the radio part of the radio-meteorograph and of his remarkable achievements towards solving difficulties. In constant consultation with Mr. Bent, the author is designing the mechanical part of the radio-meteorograph, that is, the thermo-baro-hygrograph. The author's interest in this problem was first awakened by Lieutenant W. H. Wenstrom of the United States Army. Lieutenant Wenstrom suggested, during a discussion of the author's micro-meteorograph (see Bull. Amer. Met. Soc., v. 16, pp. 1-2, 1935), the application of this principle in a radio-meteorograph. Since then, our preliminary tests have been carried out on this basis and have proven very encouraging.

The principle of our radio-meteorograph is shown on Figure 1. It is utterly simple and would present no technical difficulties were it not for the special requirements mentioned below. A rotor A turns around a center with constant angular velocity, say once every 30 seconds. Electric contacts are made with pens operated by an aneroid, a thermometer, and a hygrometer, and with a reference-pen. Each time the rotor goes by one of these pens an electric circuit is closed. The elapsed times between contacts indicate the positions of the pointers and thereby give measures of temperature, pressure, and humidity. The contacts may be sent out by the radio transmitter. At the receiving station, they can be recorded in a suitable fashion. The graph would then consist of sets of pressure-, temperature-, and humidity-readings taken approximately every 30 seconds.

Considering what has been pointed out above, the special requirements of such a meteorograph present themselves quite readily. The instrument must be accurate and sensitive. It must be extremely light, yet substantial, simple, and foolproof. It must be very inexpensive. These requirements do not exclude one another--on the contrary, simplicity, light weight, and low price can be combined very well.

The Blue Hill Observatory's research-program on sounding-balloon radio-meteorography was started but a few weeks ago. No sounding-balloon meteorograph has been completed yet, but an airplane radio-meteorograph is ready to be taken up. It was decided to experiment at first with airplane radio-meteorographs. The reason for this decision is in part that it seems more reasonable not to go to the utmost limits in restriction of weight at first. Moreover, it is considered essential to test the samples of radio-meteorographs thoroughly. Sounding-balloon meteorographs sent off at the east coast would almost invariably get lost. Therefore, testing would be very difficult and would cause considerable expense. If a radio-meteorograph, however, is used on an airplane making meteorological flights from Boston, there is no possibility for its loss and its data can be compared with the traces of the meteorograph of proven accuracy on the airplane. In addition to this, the development of an airplane radio-meteorograph is of practical significance in itself. Many of the modern airliners are cruising at altitudes of around 10,000 feet. With each commercial flight, two aerological ascensions--one after the take-off and one before landing--could be obtained. No special efforts and no other expense than the initial cost of the radio-meteorograph equipment would be involved in such measurements. Considering the large number of regular airliners in service, the use of airplane radio-meteorographs promises to become an important factor in building up our present aerological network.

The first Blue Hill airplane radio-meteorograph was constructed on the same principles that will be incorporated into the balloon-instruments. Of course, the construction had to be considerably more rugged in order to withstand the stress of vibrations of the airplane and the high flying-speed of a quick descent after a flight to great elevations. The mechanical part is separated from the radio transmitter so that the latter one may be carried inside the cabin of the airplane. Only the small stream-lined meteorograph is exposed to the air-stream.

The rotor consists of a brass disc about one inch in diameter, which is insulated on one surface save for a thin radial beam. Extremely fine points on the end of small extension-arms, fastened to a thin bimetal thermometer, to a small aneroid, and to a hair-hygrometer, slide on this disc. As the surface of the disc is absolutely smooth, no mechanical stresses other than a constant slight friction are exerted on the meteorological elements when the electrical contacts are made. No enlarging linkage whatsoever is used as the original deflections of the elements are sufficiently large to cover more than 100° each near the center of the disc. This elimination of enlarging mechanisms, with all their bearings and pivots, does away with important sources of trouble during operation. It contributes considerably to the simplicity of the instrument and it saves unnecessary weight. The contacting disc is driven by the one-minute shaft of a special clockwork, which functions satisfactorily at all temperatures down to 75° C below zero (-103° F). This clock is synchronized to a chronograph, the essential part of the recording equipment built by S. P. Fergusson of the staff of the Blue Hill Observatory.

The chronograph consists of a lerge drum rotating once a minute. A recording pen is slowly carried parallel to the axis of the drum. It writes a line on the drum which represents a perfect spiral as long as no contacts are transmitted to a relay on this pen. Each such contact causes a deflection of the pen, thus filling out the space between two spirals on the record. These markings represent the positions of the reference-pen and of the temperature-, pressure-, and humidity-pens of the meteorograph. With perfect synchronization, the markings of the reference-pen should form a straight line. As the meteorograph undergoes temperature changes of about 30° C (54° F) or more during an ascent to 20,000 feet, the clockwork speed will be slightly distorted during the ascent. This causes a certain inconvenience, but not inaccuracy, in recording the traces at the ground. However, it is felt that the present is not the time to devote too much attention to the construction of a clock of absolutely constant speed. The complex influences of the temperatures on the elasticity of the springs and the dimensions of the clockwork and of the air-densities on the movements of the escapement will be very hard to balance against each other.

The clock of the radio-meteorograph is equipped with an escapement of 312 beats per minute. Consequently, the rotating disc does not turn smoothly but jumps in frequent small jerks, each one being slightly over 1°. The present thermometer is adjusted to a range of from about 25° C (77° F) to about -35° C (-31° F). These 60° C (108° F) are distributed over a range of about 100 angular degrees on the contacting disc, that is, over about 90 jerks. In other words, the accuracy of measurement can not exceed two-thirds of a degree Centigrade. As we are accustomed to report upper-air temperatures to 0°1, the final radio-meteorograph will have to have an accuracy of 0°1. The same consideration holds true for the pressure and, to a lesser extent, for the

humidity. It does not seem impossible to have an escapement with a sufficient number of small beats. However, it seems to be much more promising to seek the final solution in a rotating mechanism that is regulated by a governor rather than an escapement. As far as the sounding balloon is concerned, the weight of the radio-meteorograph should be utilized as a driving force rather than a spring, in order to save weight. The airplane meteorograph may have a propeller-driven rotor or a small motor connected to the storage-battery.

At the time this report is written, the airplane meteorograph has not yet been tried out in actual flight. However, a demonstration with the complete sending and receiving instru mentarium at the meeting of the American Geophysical Union proved that there are no difficulties to expect. A previous flight to test a mere thermograph on the same principle as the meteorograph was very encouraging. Although the plane ascended through a solid cloud-layer of 13,000 feet, and although it was at a distance of at least 30 miles, the temperature was recorded well at the Blue Hill Observatory.

The preliminary instruments including the radio-meteorograph were built by R. D. Feiber in Cambridge. It is my pleasure to acknowledge here Mr. Feiber's unusual interest in our work and his fine workmanship.

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AURORAL OBSERVATIONS AT POINT BARROW, ALASKA, DURING THE INTERNATIONAL POLAR YEAR

C. J. McGregor

Birkeland (Arch. Phys. Sci., p. 497, 1896) regards the aurora as due to negatively charged cathode rays emanating from the Sun. Nordmann replaces the cathode rays by Hertzian waves. Arrhenius (Stockholm, Vet.-Ak. Handl., Öfvers., 1900) supposes negatively charged particles to be sent out by the Sun which, on reaching the Earth, ionize the upper atmosphere, thereby making it a good conductor for electrical discharges. The cathode rays travel at about one-tenth the velocity of light; hence they would take nearly one and a half hours to reach us from the Sun. The Hertzian waves travel at the velocity of light. Arrhenius' particles would take about 46 hours or nearly two days for transmission. Transmission-time forms an important factor when attempts are made to associate particular sunspots and solar outbursts with particular aurorae and magnetic disturbances. The solar effect is that the discharge of the difference of potential on the Earth is greatly facilitated. We have an electric current established with its consequent phenomena of aurorae, earth-currents, and magnetic disturbances. A general descriptive account of auroral theories and discussions is given by C. Störmer (Twenty-five years' work on the polar aurora, Terr. Mag., v. 35, pp. 193-208, 1930).

These are all more or less influenced by local conditions on or in the crust of the Earth, and hence they vary in intensity at different places. However, strong currents encircle the Earth--as we see in some notable cases--and may be made manifest in magnetic disturbances and earth-currents. The electrical discharges for such are the aurorae. Where do they take place? We may look upon the Sun, not as the source of the magnetic disturbance but as the medium that sets loose the bound energy residing in and on the Earth.

Generally, although not always, it is found that when there is an auroral arch its center is in the magnetic meridian. In eastern Canada and eastern United States this will be west of true north, while west of Lake Superior it will be east of the true meridian. Furthermore, if the streamers ascend from the north toward the zenith or beyond, it is found that their focus or meeting place is beyond or south of the zenith and at a point approximately where the direction of the dipping needle intersects the celestial vault. We infer then a quite close relation between aurorae and the Earth's magnetic field. It seems fairly safe to say that there is never an observed bright auroral display without an accompanying magnetic storm. Data bearing on the inverse of this statement--that with every magnetic storm we may have auroral display--are not so readily obtainable. This is because the magnetic instruments give continuous photographic registrations, which are independent of day, or night, or cloudiness, etc., while auroral data depend upon visibility, observations being limited practically to the night and a not too cloudy sky.

Tabulations of sunspots and aurorae over a long period of years show a general agreement between the maxima of the one and the maxima of the other. Aurorae, magnetic disturbance, and earth-currents are simultaneous phenomena and are due to electric currents in the higher regions of the atmosphere. As stated above, the individual intensity is to a degree dependent on local conditions, such as difference in geological formations, and all follow in a general way the

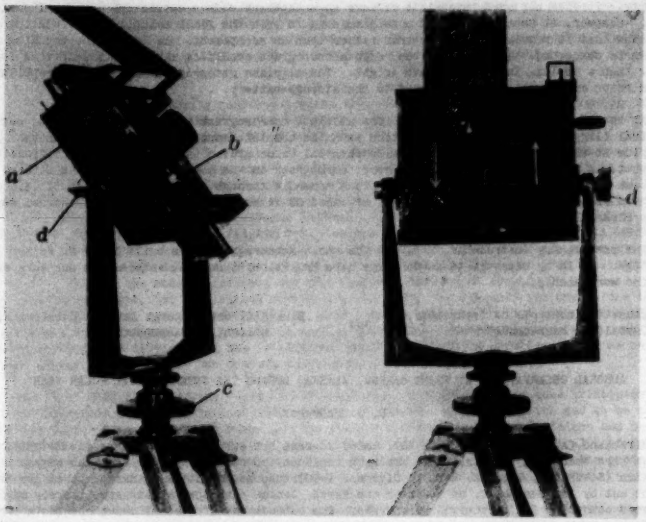


FIG. 1—AURORAL CAMERA

sunspot cycle of eleven years although the Earth intercepts but a very small portion of the Sun's radiation--less than 1/2,000,000,000.

Observational program--So far as was possible, the program of auroral observations proposed by the International Polar Year Commission was followed at Point Barrow (Alaska) station by the author. (He was without other assistants and had also to maintain the full meteorological and magnetic programs at the station.) Auroral observations were divided into three classes, namely, visual observations, sketches on prepared star-charts, and photographs. The visual observations with notes on form of displays were made at the stated hours 1, 4, 7, 10, 13, 16, 19, and 22 G.M.T. They were made regardless of weather-conditions as it is just as important to record absence of aurorae as it is to record their presence. Angular measurements were made on each end of the band or arc and usually at the center; these showed the azimuth and elevation. The apparent intensity was recorded on a scale of 0 to 4 defined as follows: Zero, no aurora visible; 1, faint aurora; 2, moderate auroral intensity; 3, bright auroral intensity; and 4, brilliant auroral display. The intensity of the 5577Å line in the auroral spectrum was usually recorded, as also the number of relevant star-chart. Under remarks, notes were made on sky-condition, on motion or movement of the display, and on its color. Sketches of the aurorae seen, together with notes regarding types, intensities, etc., were made on the star-charts. Finally numerous auroral photographs were obtained.

Auroral camera--The special camera provided by the International Polar Year Commission was used (see Supplements to the photographic atlas of auroral forms, I, published by the International Union of Geodesy and Geophysics, Oslo, 1932). Views of this camera are given by Figure 1. With this type of camera six small pictures can be taken on each plate by an arrangement that permits the objective to be placed in six different positions relative to the plate. Each position is fixed by means of a projecting point which, under pressure from a spring, falls into a corresponding hole. The pictures are taken in a definite order, indicated by the arrows on the camera. The camera is provided with a diaphragm, which is set at full opening. The focussing is done by a hand-lever (a) along a scale and the lever is clamped by a screw (b) under the lever.

The aurora consists particularly of green-yellow light, of wave-length 5577Å, and of violet and ultra-violet light, of wave-lengths 4278Å and 3914A; the ultra-violet light is very active. The photographic lenses of the camera are made thin because a great thickness of glass would

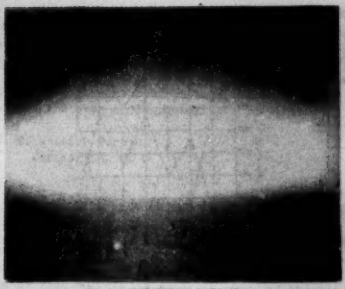


FIG. 2—HOMOGENEOUS QUIET ARC

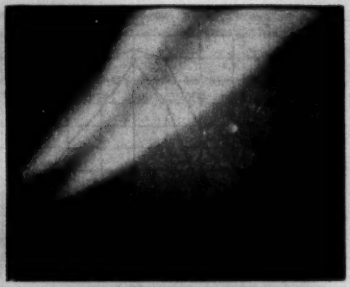


FIG. 3—PARALLEL HOMOGENEOUS QUIET ARC

FIG. 4—BANDS WITH RAY-STRUCTURE

FIG. 5—FOLDED HOMOGENEOUS BAND

absorb too much of the ultra-violet light. Good results have been obtained with small kino lenses in which the ratio of the focal distance to the diameter of the diaphragm is equal to or less than 2; a focal distance more than twice the diameter is not advisable because the lens in that case will not have sufficient light-power.

Any very rapid plate sensitive in the violet and ultra-violet, and, if possible, also in green, may be used. Barnet superior speed-ortho plates were used at Point Barrow with very good results.

Auroral observations--The auroral types are described in the Photographic atlas of auroral forms and scheme for visual observations of auroras published by the International Union of Geodesy and Geophysics, Oslo, 1930. The different forms are not sharply defined but merge into one another. Many different forms may appear at the same time. The auroral forms have been divided into two general types: (1) Forms without ray-structure; (2) forms with ray-structure.

The forms without ray-structure are subdivided into the several classes. The reproductions in Figures 2, 3, and 5 from photographs made at Point Barrow show forms without ray-structure.

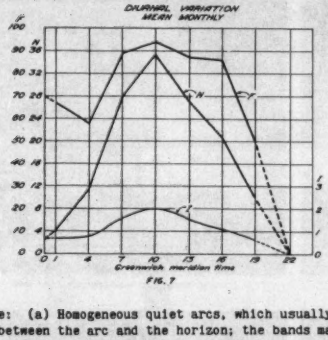


FIG. 7

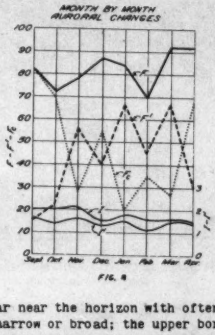


FIG. 8

These are: (a) Homogeneous quiet arcs, which usually appear near the horizon with often a dark segment between the arc and the horizon; the bands may be narrow or broad; the upper border is often diffused, but sharp along the lower border; there may appear one or more such arcs in a single display. (b) Homogeneous bands, which have not the regular shape of the arcs and are also more rapidly moving; the lower border is often irregular and sharp; sometimes the band consists of a segment of semicircular or ellipsoidal shape often forming or turning into bands with ray-structure and into draperies. (c) Other forms with ray-structure are called pulsating arcs, diffuse luminous surfaces, pulsating surfaces, and glows; these terms are self-explanatory.

The forms with ray-structure are subdivided into four general classes and are made up of short or long rays which may be arranged in different ways. The reproductions in Figures 4 and 6 from photographs made at Point Barrow show forms with ray-structure. The classes include: (d) Ray-arcs, which are usually formed from the homogeneous arc or band but are more developed and have a greater motion with short or long rays. (e) ray-bands, which resemble the ray-structure homogeneous bands but are constituted of a series of rays which may be arranged close to each other along these bands or may appear more scattered; when the band is near the magnetic zenith it may have the form of a corona. (f) Draperies and corona occur if the rays become very long, and the bands appear like a curtain or drapery; when the rays approach the magnetic zenith they appear, on account of perspective, to converge at this point and we get a corona. (g) Rays may be also isolated; they may be narrow or broad and short or long; they often appear as great bundles or like masses of rays, very often resembling curtains.

Forms with ray-structure are by far the most interesting on account of their activity, movement, and color. The predominating colors are red, green, and violet. At Point Barrow they usually appeared to the east-northeast as a homogeneous band, usually very quiet. At times the display would remain inactive for an hour, then gradually work toward the station. The north end of the arc would have a sharp rise, while the south part would have a gradual slope. At the north the ray-structure would usually form first, while at the south or southeast end, which would correspond to a position near the magnetic zenith, the corona or draperies would form.

Diurnal variation--In summarizing the results of the diurnal variation for a mean monthly graph we would have such curves as illustrated by Figure 7. The values I, N, and F are obtained by using all the monthly means for the given hours. The value of I is obtained by using the sum of all the auroral intensities divided by the total number of observations made, not counting the periods that were cloudy. This may be expressed in a formula $I = N/T^1$. N is equal to the summation of I, that is, the sum of the auroral intensities recorded. T^1 is the total number of observations. I of Figure 7 is the mean intensity for each hour plotted for the period from September 16, 1932, to April 20, 1933. Auroral frequency expressed in percentage is designated by the formula $F = 100\ (T/T^1)$, where T is equal to the number of times the aurora was actually observed.

Figure 8 shows graphs of the month-by-month auroral changes I, I^1, F, F^1, and F_c. I and F were obtained the same way as for Figure 7. I^1 represents the mean auroral intensity and may be expressed as $I^1 = (N/T^{11})$. T^{11} equals the number of observations made which includes both the presence of aurora and the times no aurora was present though recorded. F_c gives the percentage of observations obscured by clouds and may be expressed as $F_c = 100\ (T^{11} - T^1)/T^{11}$. September and October had considerable cloudiness, as also January and March.

F^1 represents the percentage of possible observations taken and may be expressed as $F^1 = 100 (T/T^{11})$. T^{11} equals the number of possible observations regardless of observations due to clouds.

Further summarizations are being made, which will include types and intensities. Besides the data that have been plotted, there are over 300 star-charts, about 2,000 angular measurements, and over 4,000 photographs to plot.

U. S. Weather Bureau,
Washington, D. C.

THE DISTRIBUTION AND FREQUENCY OF TORNADOES IN THE UNITED STATES FROM 1880 TO 1931

Charles W. Brown and W. O. J. Roberts

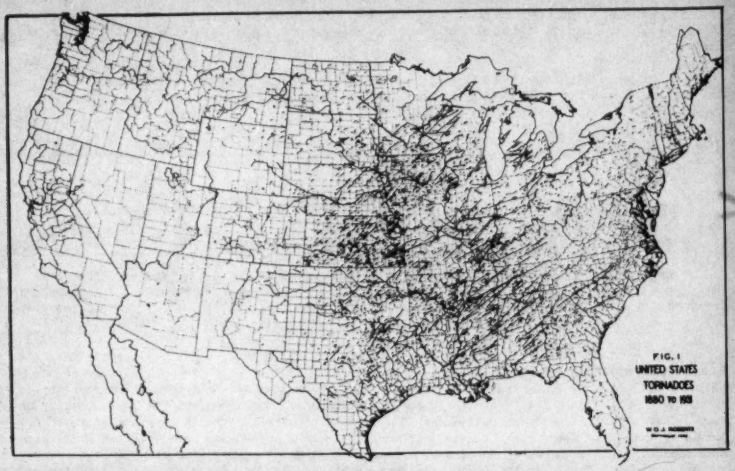
This paper is the second statistical study of tornadoes in the United States. The first paper (see Charles W. Brown, A study of the time-, areal-, and type-distribution of tornadoes in the United States, Trans. Amer. Geophys. Union, 14th Annual Meeting, pp. 100-106, 1933) covered only the last 15 years from 1917 to 1931.

The present contribution is based upon a study of all the data, which may vary in completeness in the various states and years with the personnel, contained in the publications of the Weather Bureau for 52 years from 1880 to 1931. The previous study, though for a shorter period, included 2017 tornadoes (54.1 per cent) of the total number, 3911, whereas the present study includes for the earlier 37-year period but 1894 tornadoes. Earlier graphs have been revised and the later data have been added thereto. In addition, new studies for the entire time have been made of the hourly occurrence, the frequency, and the damage possibilities of different areas, and all the tornadic tracks of the half-century have been plotted on one map (Fig. 1, which is copyrighted). These latter studies are already serving as a basis in part for revision of tornado-insurance rates. Further theoretical and statistical studies are in progress.

Distribution of tornadoes in the United States--The map of the areal distribution of tornadoes over the entire period speaks for itself. In comparison with the maps prepared of the 15 years from 1917 to 1931 there appears to be a considerable addition of the longer tracks in the eastern-central Mississippi Valley. A general increase, of course, is noted in the states most subject to tornadoes. It can be seen that the southern and western part of Texas, the northern part of Minnesota and Michigan, and eastern Kentucky and Tennessee, and in general the Piedmont and the central and northern Appalachian region, including New England, show, in the dry, in the cool and moist, or in the cool and high areas, respectively, relatively few tornadoes. The 20-inch rainfall-line (about 100° west longitude) shows a remarkable coincidence with the western limit of the tornado-distribution. A narrow bare strip from Texas to Hatteras corresponding roughly with the outer coastal plain, in part, too, with 50-inch rainfall, but more closely with the line of 250-day growing season, is in evidence. Certain minus anomalies are found throughout the map, namely: Northeastern Missouri, southeastern Oklahoma, southwestern Alabama, southern Indiana and Ohio, and northern Illinois and Indiana. Studies are in progress to try to help toward a solution of some of the questions raised by the varying intensity of tornado-occurrence in the United States. In the main, the inner southern coastal plain, the Mississippi Valley, the middle lake-region, and the eastern half of the High Plains area would include ninety-odd per cent of United States tornadoes, especially the more destructive ones.

Annual distribution--The revision of the yearly distribution of tornadoes of the two types shows plainly the maxima of both the cyclonic and convectional types occurring at practically similar periods. When the data from the earlier 37 years were compiled, we were considerably puzzled at the very low percentage of convective storms during this period. But a restudy of the maps and data gave no more convectional types and the contrast between the earlier peak and the later peak shows very strongly the preponderance of the convective type of tornado in the later years, 744, contrasted with only 117, for the earlier years.

The earlier period shows a correspondingly high gain in cyclonic types, reaching 93.83 per cent and leaving only 6.17 per cent for the convective type. If this arbitrary line of division were kept, it would show that the later 15-year period had something like 43.9 per cent of the cyclonic type, and with 56.1 per cent for the earlier 37-year period. Probably the more important thing to notice from 1891 until 1916 is the occurrence of but 18 convective tornadoes. Of course it is true that this period is the minima of all tornadoes, but the convective type does not begin to rise so rapidly from the trough as does the cyclonic. Even when the tornadoes in the minimum period were again analyzed they showed distinct relationships to well-developed cyclonic areas, and not to convective conditions.



Sub-monthly distribution--The sub-monthly distribution by 6-day periods showed some changes when the 1894 tornadoes of the period from 1880 to 1916 were added to the 2017 already plotted. The change in the curves show a marked increase in the totals in February and the last half of March, with many additions in July, August, early September, and early November. The general result is a broadening of the middle structure of the peak mainly by additions in the later heated period. The increase of cyclonic tornadoes in the heated season contributed by the earlier years inevitably shortens the peaks of the convective types and makes them less protuberant. There apparently were proportionately more cyclonic tornadoes in the last 15-year period in the colder months of November and December.

Monthly distribution by state groups--After studying the monthly distribution of the total number of tornadoes in the United States, we thought it might be of interest to see in what way the monthly curves of the separate leading states resembled or departed from the total average curve. At the expenditure of considerable time and labor, the curves of 15 of the leading states, including 3082 tornadoes, or 78.78 per cent in 1,170,000 square miles (900,000 "net" area--see later section of this paper on areal frequency), were prepared and studied. It then appeared that some of our anticipations were in part realized, for these states were placed readily in five different groups, each group varying in number, but the members having somewhat similar distributional characteristics. Certain geographical areas, it is true, showing similar monthly distribution-characteristics, did not accord, in the main, with the total curve. Again, for some unknown reason, Nebraska, though removed geographically, proved to be quite similar to Michigan and Wisconsin in the distribution of its tornadoes. Opposed to the preceding statement, Louisiana, though adjacent to both states, showed little relationship in the occurrence of its tornadoes to either Texas or Mississippi.

The first group, made up of Wisconsin, Michigan, and Nebraska, 192,475 square miles (76,804 net), with 342 tornadoes or 8.74 per cent of the total number, showed the shortest season of any of the other groups. It is the last week in March before any tornadoes are recorded in these three states and the last one occurred in the last of October. The peak occurred in early May, with a secondary rise in late September. The large proportion of the tornadoes were found in the summer months.

The second group, made up of the two leaders, Kansas and Iowa, 138,666 square miles, includes the largest number of tornadoes of any group, 816, or 20.86 per cent, in the smallest area. Two characteristics ally it with the preceding group: (1) The relatively small number of tornadoes that occur in the first three months of the year and (2) the high incidence of tornadoes that occur in September and May. A characteristic that ties it with the more southern of the states is

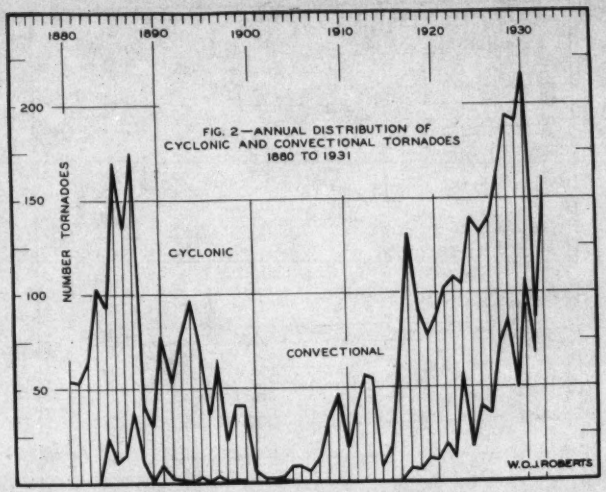


FIG. 2—ANNUAL DISTRIBUTION OF CYCLONIC AND CONVECTIONAL TORNADOES 1880 TO 1931

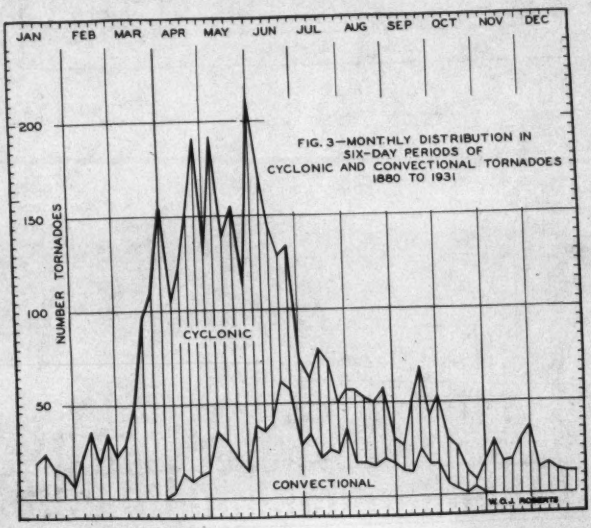


FIG. 3—MONTHLY DISTRIBUTION IN SIX-DAY PERIODS OF CYCLONIC AND CONVECTIONAL TORNADOES 1880 TO 1931

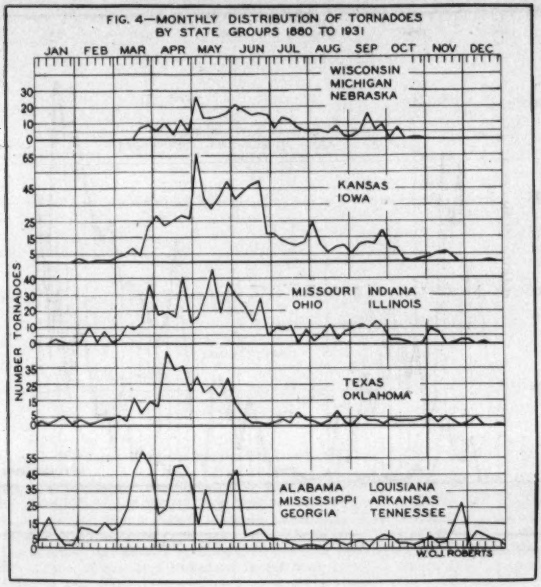
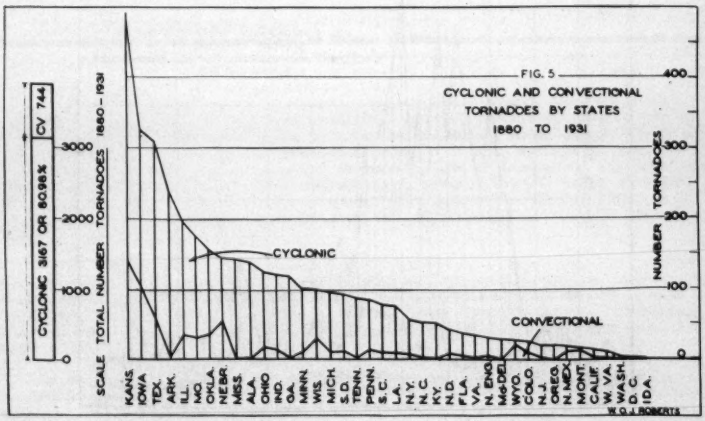


FIG. 4—MONTHLY DISTRIBUTION OF TORNADOES BY STATE GROUPS 1880 TO 1931



the small November peak. But contrary to the habit of those states, only one tornado occurs in December and January.

The next group, with 623 tornadoes or 15.92 per cent, located in Missouri, Ohio, Indiana, and Illinois, including about 200,000 square miles, exhibits from its latitudinal position earlier as well as later tendencies in the occurrence of the phenomena. Peaks occur in both March and April, as well as May. July and August, however, begin to show fewer numbers. The September and November minor peaks are still evident with several tornadoes in the winter months.

As might be expected, the fourth group, including Oklahoma and Texas, with 465 tornadoes or 11.89 per cent, has great latitudinal breadth and the largest area, 332,868 square miles (202,000 net), which entails characteristics of both the middle Mississippi Valley and the Gulf Region. On account of the large amount of its territory in the southern zone, we find that the tornado-season is well developed by the middle of March and reaches its peak the first part of April with a secondary peak the first of June. The trough occurs in July and August and, in fact, for the balance of the year the tornadoes are fairly evenly distributed. The great bulk of tornadoes occur within the three months from the middle of March to the middle of June.

The lower Mississippi Valley group, including Alabama, Mississippi, Georgia, Louisiana, Arkansas, and Tennessee, with 21.37 per cent or some 836 tornadoes occurring within their boundaries, with about 300,000 square miles, shows several peaks. The first, the last of March; the second--a little lower one, but broader--the last three weeks of April; the third, the first of June, and a smaller one in the middle of May. One of about the same magnitude, contributed mainly by the state of Arkansas, occurs in the last of November, and the smallest peak the second week in January, furnished by Alabama. The rest of the year, especially the heated season, that is, the hot summer months, again show the minima.

Summarizing this phase of the research, one might say that latitude, with the consequent northward movement of the Sun, is, in the main, responsible for the segregation of the larger number of tornadoes in the heated months. We should, therefore, expect to find the first group with high tornado-frequency beginning at least a month later than the Gulf group. In addition, the upper Mississippi Valley and the prairie states experience a greater frequency in September just as the Gulf states have more tornadoes later in November. Again, from late June into August the northern groups show a greater occurrence of tornadoes than do the more southern groups. In fact, the lower Mississippi Valley states experience their minima in these months. The further study of this phase of the subject, by including the remaining tornadoes, 21 per cent, will probably change the conclusions but slightly. In these 15 states, comprising something under a million square miles, about 79 per cent of the tornadoes of the last half-century have been located. The total number of tornadoes in these 15 states amounts to 3082, or about one tornado in 52 years for each 311 square miles, or a square 17-1/2 miles on the side.

Distribution of tornadoes by states--With the addition of about 1900 tornadoes to the graph already constructed, the relative positions of some of the states were changed. The leader, Texas, interchanges places with Kansas, formerly in the third position. Illinois moves up from eleventh to fifth place. Louisiana moves from thirteenth to the twenty-first position; Georgia from eighteenth to thirteenth place; Minnesota from twenty-third place to fourteenth; Alabama from seventh to tenth place, with other minor changes too numerous to mention. Presumably the addition of another fifty years will show very little material change in the relative order as presented with this present half-century. Probably the changes, if any, will come in the middle Mississippi Valley and the southern states, as indicated by the trend of the last 15 years.

Areal frequency--The frequency with which tornadoes may visit certain regions was demonstrated very ably by Colonel J. P. Finley in the late '80s, but only recently has the interest in this phase of the subject again been aroused.

The graphs showing the number of tornadoes occurring in the different states would be of great value if the states were of equal area, but the graph shows only tornadic curves within the differently sized political units. Obviously it would be unfair and inaccurate to contrast the number of tornadoes occurring in Texas with those occurring in Indiana one-eighth its size, in order to arrive at the frequency of tornadic visitation, say, per square mile.

One attempt to get at a truer appreciation of the tornado-intensity of any given area was to take the total area of each state, in square miles, and divide that by the number of tornadoes occurring within its boundaries. Many shifts in state tornado-frequency resulted by using this method. In addition the calculation of the "net" areas was made by eliminating areas not subject to tornadoes. This reduction of the area of certain states makes marked changes in the relative positions of the states. Thus the tremendous shift of the position of Michigan, from sixteenth

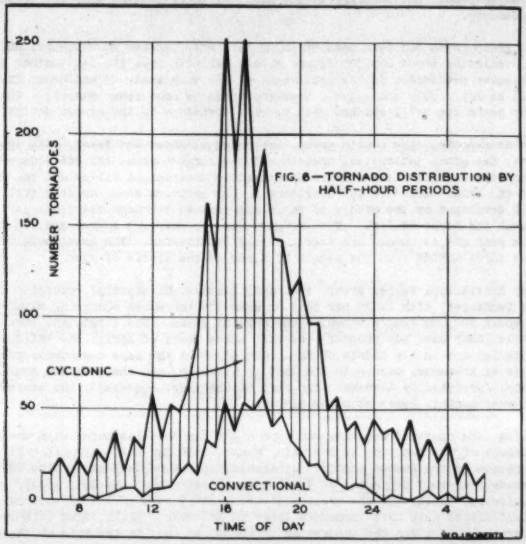


FIG. 6—TORNADO DISTRIBUTION BY HALF-HOUR PERIODS

place to sixth, is due to the fact that by a conservative estimate of the area of that state which is not subject to tornadoes, a reduction of its size by 50 per cent is thereby made. This same principle, when applied to Nebraska, reduces its area by one-third, Texas by one-half, Tennessee by one-tenth, and Minnesota by 60 per cent. Kansas and Iowa still retain their lead, and in the same order. Indiana and Michigan, with their smaller areas, now go up in frequency to fifth and sixth places, changing from twelfth and sixteenth places, respectively. Ohio moves upward to seventh place and changes position with Missouri at the eleventh place, while Texas goes down from third to twelfth place, and Oklahoma from seventh to fifteenth place; and Tennessee moves from eighteenth to fourteenth place in scale of frequency of tornadoes per square mile. This method, of course, is still quite unsatisfactory it seemed to us, because it took into consideration only one dimension, that is, the number of tornadoes occurring, disregarding their average length and width.

By another method we tried to get even a closer approximation of the probable areal frequency. The number of miles of tornado-tracks within the state of Kansas in the last 15 years, by plotting and measuring tracks in each county, amounted to 2855 miles. Dividing this number by the total area of 81,774 square miles it was found that as a result one linear mile of tornadic path occurred for each 28.66 square miles of Kansas. Thus seven-ninths of a township in Kansas might be subjected to a mile of tornado damage in the last 15 years. This result gave us the occurrence-ratio per square mile for not only the entire state, but for each county for the first period, 1917 to 1931 inclusive, which included some 54.1 per cent of tornadoes. Undoubtedly the addition of 46 per cent more will change the complexion of the tornado-distribution in Kansas, but a few comments upon the distribution of this later period may be interesting. In the first place, it appears that one northeast county on the Missouri River is twice as subject to tornadoes as any other county in the state; that the eastern three tiers of counties are much more subject to tornadoes than other sections; that a middle north-south belt, three or four counties wide, has a moderate number, with fewer tornadoes to the east and west; that in some 28 counties in the western portion of the state, tornadoes are comparatively infrequent.

But here the single dimension of the length was used without reference to the width. If we assume, for example, that there might be ten tornado mile-long tracks in the 176-yard width of every square mile, a possible new estimate might be secured, namely, that about 2.866 square miles in every 28.66 square miles might be subjected to tornadoes, or one-tenth (8,177.4 square miles)

of the area of Kansas would be traversed by a tornado one mile in length and 176 yards wide in 15 years, or about 15 per cent of every 545.16 square miles--26.34 square miles--of the area would be passed over by a tornado of such dimensions yearly.

Any such computation of the length of the tracks could be made with less error than plotting their widths. But by expenditure of a large amount of patience and a greater amount of time, the final study of such a project would result in a more firm foundation for the distribution of tornadoes by counties throughout the half-century period. Such a frequency-map would be a most accurate basis for tornado-insurance and further scientific research. The need for rezoning premium-rates for this type of insurance is evident when we realize that only two, or possibly three, rates are in use today for the entire country.

The half-hourly distribution of tornadoes--A very interesting and symmetrical graph results from the plotting of the tornado-occurrence by half-hours. The maxima of the curve rises in twin peaks at 4:00 and 5:00 p.m., with the large majority of tornadoes appearing between 2:00 and 9:30 p.m. The curve rises somewhat more abruptly, as one would imagine, from 1:30 o'clock, reaching its maximum in 2-1/2 hours, but descending more reluctantly in 4-1/2 hours from 4:00 to 9:30 p.m. Some 489 or 12.54 per cent of the reports did not show the time of occurrence of the tornado and were therefore excluded from the computation. About double the number of tornadoes occurred from 10:30 p.m. to 4:00 a.m. as happened from 7:00 a.m. to 11:30 a.m. The low trough of tornado-development as regards the time of day seems to be found between 4:30 and 6:30 in the morning. Whereas on the other hand we find that in the cyclonic type of tornadoes that may occur both in the southern states in the late winter or in more northern states in the early spring, the peak, irrespective of state or month, seems to be reached in the later afternoon. This last statement might be qualified to a certain extent in the case of Texas, where the afternoon peak is apparent, but strong subsidiary peaks occur at other periods of the day. Moreover, in Arkansas the primary peak may be reached earlier in the afternoon and the subordinate one in the evening. These qualifications, however, are based solely upon data from the last 15-year period.

It is, of course, expected that the unstable equilibrium responsible for convectional tornadoes would be developed to the highest extent during the cumulative heat-period of the late afternoon, but it is difficult to account for the predominant cyclonic tornado occurring in the 7-1/2 hours between 2:00 and 9:30 p.m. We are forced to the conclusion that there must be some relationship between the accumulation of daily high temperatures and the occurrence and passage of a cyclonic low and an accompanying tornado.

Although our study of the length of tornado-tracks is just started, the length of the tornadic track is apparently much greater in the case of the cyclonic than in the other type. Hence a tornado starting at 2:00 o'clock may occur in several localities at succeeding half-hourly intervals. So undoubtedly, since one tornado will be accounted for several times along its track that may cover several hours as the low pressure moves easterly, the peak of the cyclonic tornadoes could be foreshortened by a considerable amount. That qualification, however, will not explain the limitation of the major occurrences of all tornadoes to nearly 70 per cent between 1:30 and 9:30 p.m. Whereas the curve may be depressed from a less prominent peak, still its width between the two time-limits is significant.

Tornado-damage--In these years of billions the total property-losses due directly to tornadoes, as far as can be ascertained, give results that are not very striking. Roughly about one-quarter billion direct property-damage has resulted from tornadoes in the half-century before 1931. However, a closer inspection of the figures shows that population-density is necessarily a greater factor than number of tornadoes. The leading state in damage is Missouri, due to the two St. Louis tornadoes of 1896 and 1927, which resulted in about one-seventh the loss in the entire United States of more than a half-century. The next state is Illinois. Here again the tornadoes of 1925 and 1927 amounted to two-thirds of the total loss for that state for the entire period. Far below, in third place, is Ohio brought to that sad eminence by the Lorraine disaster of 1924. Next, with about one-third of the leader's total comes Arkansas, and then following is found Kansas, Indiana, Texas, Minnesota, Oklahoma, Iowa, Wisconsin, Kentucky, Mississippi, Michigan, Nebraska, Alabama, and Georgia in decreasing order.

With reference to the distribution of property-damage through the years one would naturally assume a greater loss in the later period with increasing density of both urban and rural population. The years 1894, 1896, 1911, 1917, 1920, and 1930 have each from $13,000,000 to $15,000,000 property-damage from tornadoes, and 1928 and 1929 suffered losses a little above or below $10,000,000 each, far above the annual totals for other years. We shall, however, have to turn to the years 1924 and 1925 to find losses of about $23,000,000, and in 1927 the figures mount to over $50,000,000, nearly half of which comes from the St. Louis disaster. The group of three years of 1924, 1925, and 1927 were responsible for more than 38 per cent of the one-quarter bil-

lion loss of the entire half-century period. Of course, one might argue that the losses of the early years might well have been doubled if the large increase in urban development had started earlier.

In contrasting the yearly frequency of tornadoes and the years of high property-damage, of course no relationship exists, excepting in a negative way. In fact, in 1911 the tornadoes were very few in number and but slightly more in 1894 and 1896 and in 1917, rising slightly in 1920, 1924, 1925, and increasing from 1927 to 1930 as a maximum.

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METEOROLOGICAL PERIODS AND SOLAR PERIODS

H. Helm Clayton

Most meteorologists are agreed that weather-conditions in certain parts of the Earth closely resemble changes in far-distant regions which may even be in different hemispheres on each side of the equator. These changes may be alike or may be directly opposed to each other. As to whether there are regular periods or cycles in weather the meteorologists are not so well agreed.

The search for meteorological periods has been very earnest and, on the whole, investigators have not been well rewarded for the great amount of work which has gone into the search. The meteorological periodicities are much more complex than was at first supposed.

My earliest work in meteorology was a search for weather-cycles. By smoothing the monthly means of pressure at certain stations in the United States with moving means of 12, it was noted

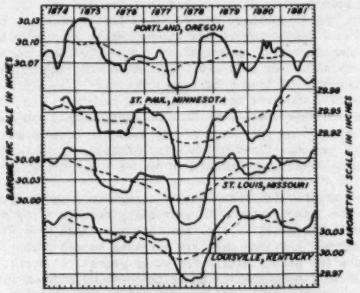

FIG. 1—TWELVE-MONTH MEANS OF PRESSURE SHOWING OSCILLATIONS OF PRESSURE OF SLIGHTLY OVER TWO-YEAR DURATION (SEE PLOT FOR ST. PAUL)

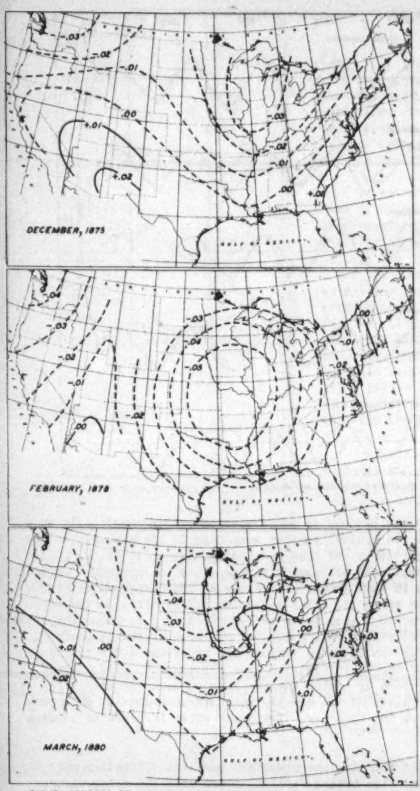

FIG. 2—CENTERS OF GREATEST MINUS DEPARTURE IN PERIOD OF SLIGHTLY OVER TWO YEARS, SHOWING MOVEMENT OF THE CENTERS OF OSCILLATION

that between 1874 and 1881 there was an oscillation of about two years in length. A copy of a plot made from these moving means for four stations in the United States is shown in Figure 1. The continuous lines are drawn from moving means of 12 and the broken lines from moving means of 25. This broken curve brings out a long-period oscillation which was combined with the shorter oscillations. The length of the shorter cycle as determined from the plot at St. Paul is about 25 months. By subtracting the 25 monthly means from the 12 monthly means a series of plus and minus differences were obtained which represent the 25-month period separated from the longer period. These departures were worked out for 16 stations as evenly distributed over the United States as possible and were plotted on outline-maps of the United States. Then lines of equal departure were drawn for each 0.010 inch. These lines showed distinct centers of maximum and minimum pressure with zero-lines, on each side of which the pressure oscillated in opposite phase.

The first minimum of pressure at St. Paul was taken as December, 1875, the next minimum as February, 1878, and the third minimum as March, 1880. These average slightly over 25 months apart. Figure 2 shows the lines of equal departure derived from the network of stations previously mentioned. It is seen that at the time of the first minimum there was a center of greatest departure near Chicago, by the time of the next minimum the center of greatest departure was near St. Louis, and at the time of the third minimum it was near Bismarck. The result of this movement was that at stations near the Atlantic Coast the phase of the period reversed between the first and third minimum. If the plots had been continued long enough, reversals of phase would have occurred at each one of the stations.

This study appeared in the American Meteorological Journal of August, 1884, and of April, 1885, and the diagrams were reproduced in the Smithsonian Miscellaneous Collections (v. 78, No. 4, 1926). I have encountered this inversion of phase in meteorological periods of every length. Attention was called to it in periods of six and seven days in Science (N.S., v. 7, pp. 243-245, 1898) and in the American Journal of Science (v. 2, p. 7, 1896) where its probable connection with solar changes was suggested. In my recent paper of World weather and solar activity (Smith. Misc. Coll., v. 89, No. 15, 1934) evidence was given that changes of phase in the sunspot-cycle were closely related to solar changes, the centers of action varying in position with changes in intensity of solar activity.

It is now evident that the increase in latitude of centers of action in the atmosphere with increased solar intensity is characteristic of all meteorological periods. This change of position brings about frequent changes of phase in the periods. For this reason all the older formulas for separating periods from each other or from fortuitous changes fail except in the case of diurnal and annual periods. In order to study other periods it is necessary to devise new methods

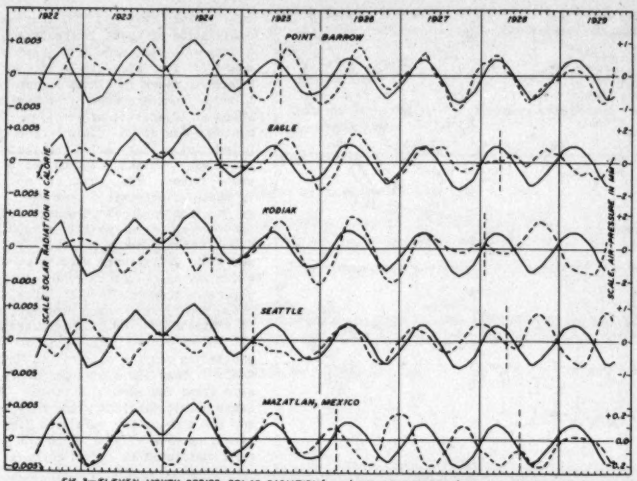

FIG. 3—ELEVEN-MONTH PERIOD, SOLAR RADIATION (——) AND AIR-PRESSURE (- - -) —MEANS OF 3

and new formulas. One of these methods is the process of successive smoothing numerically such as described above in the case of the 25-month cycle. Another method is to compute successive terms by the harmonic formula dropping one interval of time and adding another as in the case when obtaining moving averages. This process does not completely separate the periods from each other, but brings out the stronger periods in each group. For example, computing successive harmonic values for a 10-, 11-, or 12-month period in solar radiation brings out a period of about 11 months. Computing successive harmonic values for a period of 24, 25, or 26 months brings out a period of about 25 months in solar radiation. Averaging two or three of the 11-month periods together shows still more distinctly the 11-month period, and so of any other period treated in the same manner. The continuous curves in Figure 3 show the 11-month solar period smoothed harmonically and then further smoothed by taking the overlapping means of each three successive periods. The dotted lines show plots of the monthly mean air-pressures at different stations in western North America treated in the same way. The solar curve is repeated in each case for comparison.

The plots show that the pressure at all the stations sometimes oscillated directly and sometimes oppositely to the solar radiation. The broken vertical lines indicate where changes of phase occurred. Examining the curve for Kodiak, Alaska, for example, it is seen that the pressure oscillates inversely to solar radiation until August, 1924, then changes phase and oscillates directly with solar radiation until January, 1928, when it changes again and oscillates inversely to solar radiation. This change of phase does not occur simultaneously at all stations, but occurs successively later at Eagle, Seattle, Point Barrow, and Mazatlan. Plotting the departures at 30 or 40 stations in North America on maps shows clearly that the change of phase is connected with movements of opposing centers of action like those shown in Figure 2. In both hemispheres north and south of the equator these centers move toward the equator with decreasing intensity of solar activity and away from the equator when solar radiation is increasing. The oscillations decrease in amplitude when the centers are moving toward the equator and increase in amplitude when moving toward the pole. These relations have been found to be true for meteorological periods of all lengths from periods of a few days in length to those of many years. Inversions of phase occur when the zero-line between the opposing centers of oscillation passes over a station.

In line with this idea C. J. Kullmer finds that the tracks of barometric depressions move poleward with increasing solar activity in the 11-year sunspot-period.

Canton, Massachusetts

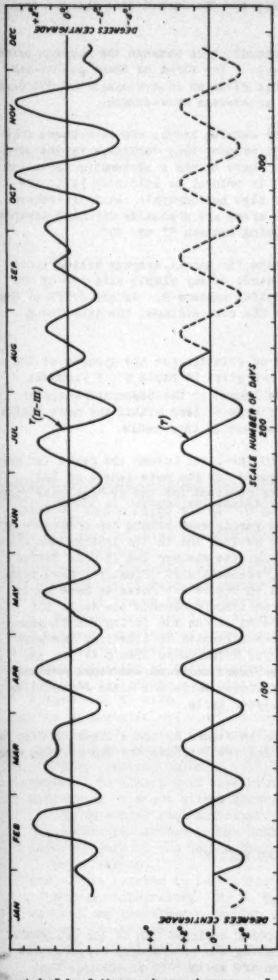

FIG. 1 — 27-DAY PERIOD IN TEMPERATURE-DATA FOR OSLO, YEAR 1916

THE 27-DAY PERIOD IN TEMPERATURE-DATA

K. F. Wasserfall

During my work with the periodic phenomena of geophysical data I have in various papers pointed out the importance of these phenomena for the understanding of the variation in temperature-data. In the temperature-data of Oslo the 27-day period is nicely developed, as will be seen from Figure 1.

To get a clear picture of each periodic series, I have tried to separate them by aid of the well-known Koch-Blanford method (see On periodic variations in terrestrial magnetism, Geofys. Pub., v. 5, No. 3, 1927). Calling the original daily mean figures observed in Oslo O and the successively smoothed data I, II, III, etc., we get the separated periodic series by subtracting corresponding data in each set from the preceding thus: (O - I), (I - II), etc. The smoothing in this case was performed with 5, 13, and 27 figures in the successive means, by which process we gradually eliminated these periodic series. The 27-day series--being of the type (II - III)-- is shown graphically in Figure 1. It represents this variation in the temperature-data for Oslo for the year 1916.

Various authors are still inclined to associate the 13.5-day and the 27-day periods with the Moon. There seems, however, to be no doubt that this periodicity must be considered one of the many terrestrial effects of the variation of the solar activity. In this special case the periodicity depends on the well-known fact that the Sun's activity tends to be concentrated longitudinally about comparatively narrow areas, showing but small displacement during the year.

As will be seen by the illustrations which Wolfer uses in Astronomische Mitteilungen, there is always one main area of activity and a secondary one--the interdistance between them being about 180°. This longitudinal distribution of the active areas on the Sun, in connection with the rotation, is thus responsible for the 13.5-day and the 27-day periods we observe in geophysical data.

The 27-day period of the temperature-data of Oslo for the year 1916 is drawn in the upper part of Figure 1. Those who have worked with the periodic phenomena of geophysical data have of course been aware of the occasionally occurring phase-changes. To get a correct value for the average wave-length of the oscillations, it is very important to get hold of these phase-changes. In Figure 1, I have, therefore, below the curve T(II - III) put a synthetic representation, where the interdistance between each maximum (minimum) is 28.5 days--the constant amplitude being 4°0. To mark out direct and inverted oscillations I have alternately used full and dashed lines. Experience shows that usually a positive relation to solar activity is dominating during the summer half-year, and negative during the

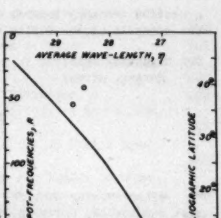

FIG. 2—RELATION BETWEEN WAVE-LENGTH OF 27-DAY PERIOD AND HELIOGRAPHIC LATITUDE OF CIRCLES OF SUN WHERE SUN-SPOTS GRADUALLY APPEAR DURING THE 11-YEAR CYCLES

winter half-year (the full line means a positive relationship and the dashed line means a negative relationship).

The average wave-length has been based on the total interdistance between the maximum point of the first and the last oscillation of the curve $T_{(II - III)}$. The first of these points may be assigned to February 19 and the last to November 18. This gives an interdistance of 273 days, which--divided by 9-1/2 oscillations--results in 28.7 days as average wave-length.

In a similar way I have calculated the wave-lengths for several years, and have found that they vary between 30 and 26 days. I have often asked myself whether this variation in the wave-length is due only to errors in the measurements or whether there exists a systematic variation from year to year. If such systematic variation exists, it is natural to attribute it to the fact that every 11-year cycle starts with an active area in high heliographic latitude--between 40° and 50° north and south. During the cycle these active areas are gradually drifting towards the Sun's equator--the most frequent area for spottedness being between 7° and 30°.

The data we should have to answer this question are those for annual average heliographic latitudes of the active areas, but not having such data at hand, we may simply make use of the yearly mean values for frequency of spottedness--the Wolf-Wolfer numbers R. As the drift of the active areas goes from the minimum--through the maximum--to the next minimum, the data for R must be used in the manner shown in Figure 2.

According to Warrinton and Stratonoff the synodic time of rotation for the girdles of the Sun, where the spots and the faculae appear, respectively, are given in Table 1. I find the figures for the average wave-length of the temperature-cycles for the different years vary more or less within the same limits as those given in the last column of this table.

Table 1

Heliographic latitude	Periods	
	Sun faculae	Sun-spots
° °	days	days
0-10	26.4	27.0
10-20	27.2	27.4
20-30	27.4	28.2
30-40	28.2	29.0

Table 2

Year	η	R	Maximum
1904	28.5	42	towards
1916	28.7	55	towards
1930	28.2	36	from
1931	27.1	21	from
1932	27.2	11	from
1933	27.0	6	from

In Table 2 I have put in the first column the years for which I possess average annual figures for the wave-length of the "27-day" variation. The data obtained for the average wave-length are entered under the heading η. In the third column we have, under the heading R, entered yearly mean values for frequency of sunspottedness, according to Wolfer, and in the last column the words "towards" and "from" indicate whether the 11-year period is increasing or decreasing, respectively. Finally I have plotted the values of η and of R in Figure 2. Above we have horizontally the scale for η which also represents the scale for time of rotation for the girdles of the Sun during the 11-year cycle; the arrow indicates the direction of time from one maximum to the next. The scale for R increases from 0 to 100 and then decreases again to zero. Vertically on the right are the data for the heliographic latitude, which the areas of activity gradually pass during one 11-year cycle.

Judged from what is seen in Figure 2, there seems thus to be a decided tendency towards the suspected relation between η and the latitude for the girdles where the sunspots appear during each cycle.

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THE AIRPLANE AS A FREE-AIR SOUNDING MEDIUM

Horace R. Byers

(Abstract)

After showing that the airplane in proper hands and properly equipped can be the quickest, most dependable, and most economical means of carrying a meteorograph to ordinary heights, the required standards for obtaining flights of a reliable nature are given. It is obvious that these standards can be met only by operators with experience and equipment comparable to those of the commercial air-lines. Since increasing use of the reports is being made by the air-lines, they should be encouraged to cooperate by making the flights at reduced cost to the Government and increased benefit to themselves through providing flights in unfavorable weather. A cooperative effort of this nature has already been proposed by Transcontinental and Western Air Lines.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

AMERICAN GEOPHYSICAL UNION

Sixteenth Annual Meeting

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

Washington, D. C.
April 26, 1935

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FURTHER OZONE-MEASURES AND THEIR CONNECTION WITH THE SUNSPOT-CYCLE

F. E. Fowle

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A fourth report on atmospheric ozone follows. The amount of the Sun's zenith-radiation absorbed in the Chappuis yellow ozone-band (roughly 0.45 to 0.65μ) in the passage of that radiation to the ground is taken as an indicator of the amount of ozone present in the atmosphere. The unit used for measuring this absorption is 10^{-3}cal/cm^2/min.

The first report (Smithsonian Misc. Collections, 81, No. 11, 1929) described the theory and method used in reducing the observations. Plots were shown of the amounts of ozone observed at Harqua Hala, Arizona (latitude 33°8 north, altitude 1721 meters); at Table Mountain, California (latitude 34°4 north, altitude 2286 meters); and at Montezuma, Chile (latitude 22°7 south, altitude 2711 meters. Balanced against these there was a plot of mean annual Wolfer sunspot-numbers

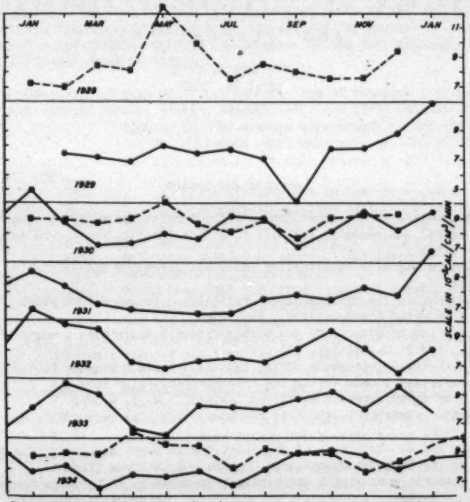

FIG. 1—OZONE AT MONTEZUMA, CHILE (——) AND AT TABLE MOUNTAIN, CALIFORNIA (– – –)

corresponding to the days of ozone-observations. The conclusion seemed then quite warranted that there was a close correlation between the spot-numbers and the ozone--the greater the spot-number, the greater the amount of ozone. The data indicated a smaller amount of ozone above Montezuma as should have been expected from the observations of others for small latitudes.

With last year's report (Trans. Amer. Geophys. Union, 15th Annual Meeting, pp. 160-162, 1934), a changed aspect of the relationship between ozone and the spot-numbers had become notable. The Table Mountain ozone-measures during seven years of diminishing spot-numbers (annual means) showed a slow rise instead of a considerable fall. Further, the reduction of the data during 1933 at Montezuma showed three times as much ozone as would have been expected from the earlier observations during 1923 for the same place.

The cause of this modification of previous results must be one affecting both Table Mountain and Montezuma, causing generally larger values of ozone.

It happened that, with the beginning of our observations at the Table Mountain station, a new method was employed for the measurement of our bolographic solar-energy curves. Formerly a

smoothed line had been drawn through the serrated energy-curves so that about as much of the curve's serrated area lay above as lay below. This, in a manner, diluted the spectrum-energy of radiation pertaining to ozone with that from the adjacent regions in the spectrum. At Table Mountain we no longer draw such a smoothed curve through the ozone-region but use points on the energy-curve itself giving practically a purer spectrum and hence greater values for ozone-measures.

Coincident with this change, instead of making measures at definite prismatic deviations in the spectrum, they are made at definite wave-lengths. These wave-lengths were obtained by using solar lines as near as possible to the earlier prismatic deviations. Some small correction was made to reduce values at the new places to the older evenly-spaced deviations. It was found from the appearance of the plotted Montezuma data that this same new method was in use there from 1929 on.

In Figure 1 are plotted monthly means of the new reductions of three years at Table Mountain and of seven years at Montezuma. They show the usual yearly run. It is perhaps too early to draw any definite conclusion from a comparison of the yearly means of ozone above Table Mountain and Montezuma with the annual sunspot-numbers as to what relationship, if any, exists between sunspots and ozone.

I should not close without expressing my gratitude to Severlina Fowle for her arduous task of plotting over 8000 observations and making many of the subsequent reductions.

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CORRELATIONS OF AURORAL AND MAGNETIC ACTIVITY AT LITTLE AMERICA, FIRST BYRD ANTARCTIC EXPEDITION

C. C. Ennis

Relationship between the aurorae and magnetic disturbances has been the subject of much study and investigation. Whether there is a real auroral effect on magnetic values is a question about which there has been much discussion as well as skepticism. In this paper is presented a brief resumé of the results obtained from an analysis--a purely statistical analysis--of concurrent magnetic and auroral values obtained at Little America by the First Byrd Antarctic Expedition.

It is common-place knowledge that the polar regions are ideal for such an investigation because of the frequency of aurorae, although the inevitable "fly in the ointment" often appears because of the well-known unfavorable climatic conditions which may cause serious interruptions in both the auroral and magnetic observational programs. Also in polar regions magnetic oscillations are at times so great that the magnetic traces go beyond the limits of registration on the magnetograms. Then, too, while the self-recording magnetic instruments are continuously operating, barring unavoidable interruptions occasionally, aurorae can be seen only for a short period during the local winter months of darkness, and during this period there are intervals, sometimes for days, when aurorae, if present, could not be seen on account of cloudiness.

The auroral program at Little America, maintained from April 3 to October 1, 1929, provided for visual observations at every half-hour during each day, at which times were noted the form, intensity, direction, altitude, and color of the aurorae, as well as the meteorological conditions. Both the auroral and magnetic programs were under the direction of F. T. Davies of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Mr. Davies made an interesting and informative discussion of these auroral observations (Terr. Mag., v. 36, pp. 199-230, 1931).

Continuous registration of the magnetic variations, subject to some interruptions, was carried on from June 4, 1929, to February 8, 1930, so that from the former date to October 1, 1929, there were concurrent records of magnetic elements and aurorae, although on account of the infrequent observations of aurorae during September, due to the increasing number of daylight hours, it was decided to base the present discussion only on the data for June, July, and August. None of the months nor days of the month were complete for reasons already emphasized, there being a total of only 62 incomplete days during the period. From these data were gathered 1582 pairs of simultaneous auroral and magnetic values, the compilations and reduction of which were made by W. F. Wallis of the Department.

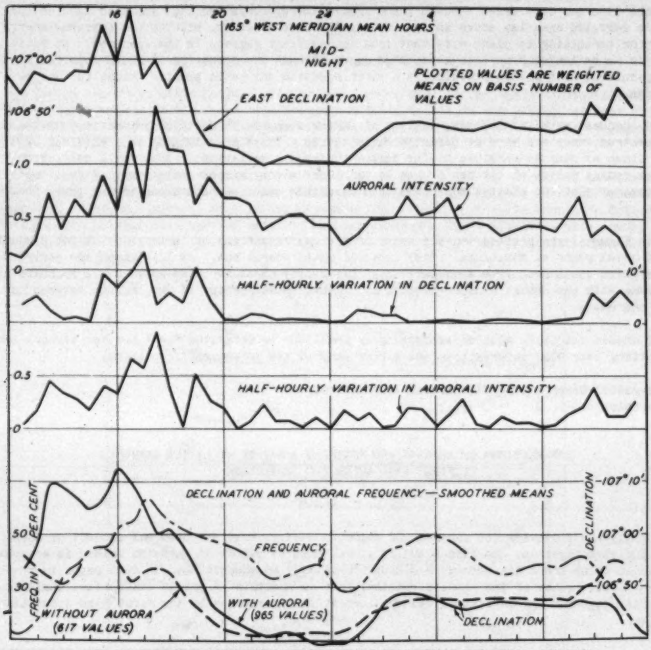

FIG. 1—COMPARISON VALUES MAGNETIC DECLINATION, AURORAL INTENSITY, AND AURORAL FREQUENCY, LITTLE AMERICA, JUNE TO AUGUST, 1929, FIRST BYRD ANTARCTIC EXPEDITION

For the purpose of this analysis it was deemed sufficient to depend only on the intensity of the aurorae as the auroral function and on the declination as the magnetic function. The auroral intensity, as estimated by the observer, is based on the arbitrary scale, 0 to 4--0 = no aurora, 1 = faint, 2 = moderate, 3 = bright, and 4 = brilliant displays. Since the various ratings depend only on the judgment of the observer, the personal equation must enter somewhat largely.

Now that we have come into possession of these 1582 pairs of coincident auroral and magnetic values, the question is as to how best to treat them. Just a qualifying word about the expression "coincident values." The reduced magnetic values represent the hourly means and are considered as applying to the middle of the hour--"centered on the half-hour," as we commonly say. The auroral values, however, were obtained for each half-hour during the day. This would give us, assuming a complete day, 48 auroral values and 24 magnetic values for a given day. This deficiency in the number of magnetic values was obviated by interpolating over consecutive hourly values, thus providing corresponding magnetic values for each half-hour. It is to be admitted that this procedure does not provide a series of independent values of one of the variables. A better plan would have been to scale the magnetic values from the magnetograms for the instant of observation of the aurora, but on account of the multiplicity of the auroral values it was not deemed feasible.

To determine possible auroral effects some investigators have used a so-called "normal" magnetic day as a criterion, differences between the normal-day values and the observed values being attributed to the auroral effect. There arises the question, what is a normal day? It would seem that such an expedient is open to criticism. This normal day is commonly derived by

taking the average of a group of selected days--days magnetically quiet--and recourse is naturally to the five international quiet days selected for each month.

However, for the Little America data, there were only eleven international quiet days available during June, July, and August. On seven of these days there were 94 occurrences of the aurora. For the other four days the auroral log records no aurora visible, but on these days there was cloudiness ranging 8 to 10, on the usual cloudiness-scale of 0 to 10. Thus our normal-day standard, itself contaminated by possible auroral effects, could not be considered a well-chosen basis for comparison. In order to get away from arbitrary assumptions, two methods were used: (1) Simple correlation; (2) comparison of magnetic values for times when aurora was observed with those when no aurora was observed. In making the correlations, separate tabulations were made of the half-hourly coincident values of the magnetic declination and of the auroral intensity throughout each usable day for June, July, and August. The means of these two sets of half-hourly values, representing the diurnal course of the declination and of the auroral intensity, gave us corresponding pairs of values of the two variables to be correlated. Similarly, correlations were made (1) for the half-hourly changes throughout the day without regard to sign, (2) for the interdiurnal variability or changes from day to day, and (3) for all the separate pairs of coincident values of the variables. The results of these correlations are summarized in Table 1.

Table 1--Summary correlation-coefficients (r) and probable errors (p), auroral intensity and magnetic declination, Little America, June to August, 1929

Feature and month	Interval in 165° west meridian hours			
	12 to 11.5		14 to 10	
	r	p	r	p
Diurnal variation				
June	0.44	±0.08	0.47	±0.08
July	0.37	±0.08	0.64	±0.06
August	-0.23	±0.12	-0.11	±0.10
June-August	0.39	±0.08	0.61	±0.07
Half-hourly changes				
June	0.09	±0.10	0.07	±0.10
July	0.75	±0.04	0.75	±0.05
August	0.19	±0.09	0.19	±0.10
June-August	0.64	±0.06	0.71	±0.05
Interdiurnal variability				
June	0.45	±0.13	....	....
July	0.23	±0.13	....	....
August	0.04	±0.19	....	....
June-August	0.25	±0.09	....	....
All coincident values				
June-August	....	....	0.15	±0.02

Table 1 shows a considerable diversity in the correlation-coefficients, some indicating no correlation worthy of consideration, others indicating a fairly high degree of relationship, notably those for July. With regard to some of the lower values of r, the ratio r/p might have some significance.

The observational data used in the correlations for the period June to August are shown graphically in the curves of Figure 1. It will be seen that, on the basis of hourly ranges, the greatest magnetic and auroral activity occurs from about 9^h to about 19^h; also that the times of maximum and minimum values of the two elements are fairly coincident, the former occurring about 15^h to $18^h$and the latter about midnight. It is to be noted that there is a fairly rapid increase in the declination just after midnight, the same being reflected in a corresponding rise in the auroral-intensity curve. The curves for the values of the declination for times when the aurora was observed and for times when there were no occurrences indicate, generally speaking, that the declination is greater at those times when the aurora was present than it is for the times when no aurora was seen. Regarding the exception to be noted at about noon, it may be stated that the auroral data for this time were relatively very few, and might justifiably have been omitted. In this connection it is interesting to note the following summary of weighted mean values of the declination and corresponding mean values of auroral intensity.

Auroral intensity	0	1	2	3	4
Declination (106° east +)	46'.4	46'.4	52'.3	57'.1	59'.5
Number of values	838	449	129	21	8

The curve designated "Frequency" was derived from the ratio, expressed in per cent, of total auroral occurrences to total times at which aurorae could be seen if present. The close paralleling of this curve with the auroral-intensity curve probably is of statistical rather than natural significance.

By way of summarizing, it may be that these data are not sufficient for definite and specific conclusions concerning auroral effects on the Earth's magnetism. For Little America the following facts seem to be established concerning the two phenomena investigated: (1) The greatest activity in each, on the basis of hourly ranges, occurs from about 9^h to about 19^h; (2) the times of maximum and the times of minimum values are in good agreement for both; (3) on the basis of averages, the declination-values for times when aurorae were present are greater than those for times when no aurorae were observed; (4) a more or less loose, in some cases fairly high, correlation is shown.

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NEED FOR MORE DETAILED MAGNETIC OBSERVATIONS SHOWN BY INCREASING APPLICATION OF RESULTS

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At the present time we are confronted with the establishment of a policy of national planning, one of the objects of which is the conservation of natural resources. The committees making such studies find themselves seriously hampered right at the outset by the lack of sufficient scientific data. The great need is for maps--not only topographic, but also geological, geophysical, and other maps. The report of the planning committee for mineral policy, National Resources Board, states that the "arts of exploration, mining, and metallurgy must be fostered so as to offset the progress of exhaustion and the growing obstacles of nature" [1].

In the art of geophysical exploration, which includes magnetic, gravimetric, electrical, and seismic methods, the magnetic method is the cheapest and fastest in application. It is the oldest of the geophysical methods, having been used in Sweden as early as 1640 for the prospecting of iron ores. At that time a crude form of compass was used, but later improvements brought out the present so-called magnetometers designed for relative measures of vertical and horizontal intensity, which have been adapted to prospecting for oil, gas, and gold as well as iron ores. Except in the case of iron ores, the magnetic method is more in the nature of a reconnaissance-survey, serving to indicate promising regions where the other more expensive types of prospecting will be worth while.

The accuracy of location of minerals by geological methods depends on the accessibility of the formations and on the number, depth, and spacing of bore-holes. Most bore-holes go to depths of 7000 feet or less, while data by magnetometer, torsion-balance, and seismograph may be obtained down to depths of two to three miles. Geophysical discoveries supplemented by geological knowledge are more apt to be productive than purely geological discoveries. In the case of oil, Dr. Heiland shows 55 per cent of geophysical discoveries productive against only 12 per cent for geological discoveries [2].

In view of these facts, it seems that this is an excellent time to attempt an appraisal of magnetic surveys in the United States, however made. It is not easy to do this except for the work of the United States Coast and Geodetic Survey, since many of the results of others have not been made public, and even if made public, could not be coordinated for various reasons, the principal one being the lack of sufficient absolute stations to which the work could have been tied. The author has, for the past year, been charged with the duty of studying the magnetic survey of the United States, its effectiveness for the various purposes to which it may be put, and possible extension and applications of practical value.

Even though it is recognized that observations at county seats (the basic distribution of stations of the existing magnetic survey) do not form an adequate basis for relation to geological structure, attempts have been made notably by W. P. Jenny [3] and George B. Somers [4], each of whom has supplemented the survey to some degree by additional work.

Important facts relating to the present magnetic survey are as follows: Areas as great as 30,000 square miles in the United States are without an observation; 6,000 stations for 3,000,000 square miles varying from one station in 50 square miles in Delaware to one in 2,000 square miles in Wyoming and Arizona. In comparison European countries vary from one station in 50 square miles

to one per 200 square miles. As to accuracy, some of the original data date back 50 years or more when instruments for giving the present requirements of accuracy were not available.

It is quite important for the United States Coast and Geodetic Survey to know the limits of an area of local attraction, not only for its nautical charts, but also for furnishing information to the surveyor. With such sparsity of stations as exists at present one cannot say whether a region is disturbed magnetically or not, as has been shown in many instances. Recently in the replacement of a station in Pennsylvania which gave a normal value of declination, several possible new sites were tested and all found to show marked local attraction; thus information as to declination given out for that county was based on a station which accidentally gave a normal value and was therefore decidedly misleading.

Donald C. Barton as Chairman of the Research Committee of the American Association of Petroleum Geologists [5] and W. T. Thom, Jr., as Chairman of the Special Committee on Geophysical and Geological Study of Continents of the American Geophysical Union [6], present the following as interesting problems to be solved with the aid of magnetic and other geophysical surveys. "Do the Appalachians extend southward under cover and is there a connection between them and the Ouachita Mountains?" Dr. Barton asks "What is the configuration and position of the northern and eastern flanks of the Sabine uplift of Louisiana and Arkansas?" "What is the configuration and extent of the buried mountain ranges known to be present beneath the Panhandle of Texas and beneath other parts of the Great Plains region?" These questions are of importance because major oil and gas pools are tied up with them. M. C. Alexanian, engineer-geophysicist, says that very often the geologist is especially interested in obtaining for his investigations the absolute value of the terrestrial magnetic field [7].

Where large areas are involved as is the case in the questions above, magnetometer surveys to be of the most possible use should be tied in frequently with absolute observations and, in addition, a temporary magnetic observatory should be set up in the center of such areas to take care of the diurnal variation for work both in absolute measurement and by magnetometers. This latter is of importance because without such control the absolute observations have to be reduced by estimates of the diurnal variation based on records at United States Coast and Geodetic Survey magnetic observatories in Arizona and Maryland. Also with such a set-up it is possible to make better progress with the magnetometer by considerably lengthening the working day from five to about eight hours.

Recent work in this field shows much promise of results. The work of Dr. Lee and Dr. Swartz in the helium-reserve district of Amarillo brought out very clearly the configuration of the basement-rock by magnetometer readings at intervals of one mile. In the foreign fields similar success has been met with. A notable example is the tracing for a distance of 18 miles seven beds of magnetic shales under heavy cover on the Witwatersrand, South Africa. The gold-bearing reefs bear a known relation to these magnetic shales [8].

W. F. Prouty, G. R. MacCarthy, and J. A. Alexander of the University of North Carolina, Department of Geology [9], have made some very interesting discoveries as a result of a magnetometer survey over portions of the coastal plain of the Carolinas. Quoting Dr. Prouty: "The magnetometer readings have given much valuable information concerning the depth, character, and structure of the crystalline rocks underlying the coastal plain. The more steeply-inclined fall-zone peneplain of the buried crystallines has been shown to give place to a less steeply-inclined buried peneplain farther inland; the buried Triassic Basin near Florence, South Carolina, has been outlined and traced northeastwardly into North Carolina; other linear high magnetic areas of unusual character have been mapped."

Incidentally, Dr. Prouty's magnetometer party has given further evidence tending to prove that the Carolina bays and elliptical lake basins are of meteorite origin. They have found anomalies as high as 400 and 500 gammas adjacent to these features and always in the same relative position. It will be recalled that in the case of Meteor Crater of Arizona both magnetic and electrical observations showed the location of the buried body to be under the south rim of the crater. The magnetic anomaly in this case was only 40 gammas, a body having been located, as indicated by these surveys, with the drill at a depth of 1400 feet.

In California, under the direction of Beno Gutenberg, observations are being made with magnetic instruments for locating the extension of the San Andreas Fault [10]. Here we have a connection between seismology and magnetism and engineering construction. Where faults, known or unknown, can be located by this method, they will at least indicate where seismic action might occur and such sites can be avoided for structures. The present status of earthquake-prediction is a mere statement that wherever earthquakes have taken place in the past they are apt to take

place in the future. Occasionally, however, an earthquake of considerable force takes place in regions which have previously been entirely free of them, at least as far back as our earthquake-history extends. The Baffin Bay earthquake of 1933, which sent a flood of icebergs into the North Atlantic, stands by itself for that region. The earthquake at Charleston, South Carolina, in 1886, which was felt over an area of 3,000,000 square miles, occurred in a totally unexpected region from a geological standpoint. A detailed magnetic survey in such an area might bring out the existence of certain buried structures with which to connect the earthquake.

In the purely theoretical field, the following is an interesting example of possible use of the magnetic survey of the United States. The late L. A. Bauer and W. J. Peters [11] of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington made an investigation of the magnetic field of the Earth, the results of which were published in 1920 and 1923. They accounted for 97 per cent of the total field, but three per cent had to be considered as non-potential and not capable of direct measurement. It was accounted for, however, by a line-integral carried around the Earth which failed to close by approximately the required amount.

Recently magneticians have expressed the desire that this be again checked by carrying a line-integral around several areas in the United States sufficiently free from magnetic disturbance. However, the magnetic survey as carried out to the present time does not provide sufficient data on which to base such an investigation.

It is not my purpose to outline a program, but it seems reasonable that the United States Coast and Geodetic Survey should extend its survey until a spacing of stations is obtained that corresponds with European conditions. This can undoubtedly be done without interference with and, in fact, with enhancement of existing work. In such work the function of the Bureau would be precise measurement and not interpretation except as the two may be inseparable in producing an adequate survey. It would not be in competition with consulting geophysicists, but would point out regions which might repay more detailed investigations. With the excellent work being done in the chemical fields in furnishing the manufacturing world with new alloys, the worthless raw material of today may suddenly become of the utmost importance. Materials which are of a magnetic character or bear a known relation with adjacent magnetic material may be located by a detailed magnetic survey and be available for all future uses.

One frequently hears or reads the statement that some invention has practically replaced the magnetic compass. That this is far from the practical truth is evidenced by the continued use of the magnetic compass on land, sea, and in the air. The surveyor's compass is particularly adapted for reconnaissance-surveys, for areas which are heavily wooded or not of much value, and in rerunning old boundary-lines originally surveyed by the compass. It is interesting to note that a manufacturer of a popular type of surveyor's transit states that 95 per cent of transits sold by him are equipped with the magnetic compass, in spite of the fact that a liberal reduction is made when the compass is omitted. Accurate modern surveys, of course, omit the use of the compass entirely unless some legal requirement makes it necessary to determine the magnetic courses along with the true courses.

Magnetic observations on the oceans ceased in 1929 with the loss of the Carnegie. The positions and directions of the isogonic lines over three-fourths of the surface of the Earth are now dependent on methods of extrapolation. Great Britain has decided to build a non-magnetic vessel to resume and continue this work, but it will be many years before it can be brought up to date.

Due to the expense involved many vessels of the merchant marine are not equipped with gyro compasses, and even with such equipment one or more magnetic compasses are provided as standbys. Mechanical devices are not infallible, especially when dependent upon an electrical power-supply.

In many harbors of the United States there is excellent opportunity for vessels to "swing ship" on ranges formed by objects on shore. The master of a vessel can use such ranges in cloudy weather to determine the condition of his standard compass after taking on or discharging cargo when otherwise he might be delayed for lack of sunshine as in the case of determining the deviations by bearings on the Sun. The United States Coast and Geodetic Survey publishes the true and magnetic bearings of such ranges for that purpose. In such cases more intensive declination-observations are made to be certain that no local attraction exists, which would interfere with the use of such ranges.

An example is the work recently completed at Jacksonville, Florida. The St. Johns River is so sinuous that in proceeding from the sea to Jacksonville, a distance of 24 miles, no less than 20 different courses are steered which are well distributed over the various points of the com-

pass. The true azimuths of the channel-ranges were determined by triangulation or direct observations and sufficient declination-observations were made to show absence of any marked local attraction.

From such a series of observations over a round trip, one can construct a curve of deviations, such as the Napier diagram, and thus obtain deviations for the entire compass-card. In the case of a vessel taking on or discharging cargo at Jacksonville, the outbound values would not furnish sufficient values for a complete curve but would indicate to the master of the vessel whether compensation of the compass was necessary before proceeding to sea. Similar work is contemplated in other harbors.

In aircraft the complete gyro compass will not function due to centrifugal accelerations, and in its place we use the directional gyro, which on account of friction in its bearings has to be reset by the magnetic compass every 20 minutes or so. Radio-compass homing devices, radio ranges, radio phones, all fail, or their range becomes greatly impaired when they are most needed, that is, in thunderstorm, snow, fog, etc., when visibility is reduced, and under bad conditions of static. Under favorable conditions radio ranges in the United States are good for a distance of 100 miles but under bad conditions of static, etc., only for a distance of 30 miles. In the case of bad electric storms, they are of no use, since the pilot is then forced to ground his antenna in order to prevent damage to the plane by being struck by lightning. He is then entirely dependent for his course on the magnetic compass.

In addition, aerial navigation has reached the stage of accuracy that consideration must be given to accurate values of magnetic declination. Harold Gatty [12] claims an accuracy of one-half degree in dead-reckoning with the use of the aperiodic compass, drift-meter, and other instruments in maintaining a course over water without reference to landmarks. The Coast and Geodetic Survey is extending its observations to include determinations of declination at the compass-testing platforms of airports, for use in compensating the airplane's compass and determining its deviations at frequent intervals. The latter change from time to time, due to changes in the magnetic conditions of steel members of the fuselage and also suddenly as a result of introducing magnetic cargo or after being struck by lightning.

In addition to all these practical uses which indicate the need of a more detailed magnetic survey, such a survey will add greatly to the purely scientific knowledge in furthering the studies of the Earth's magnetism which is so intimately connected with aurorae, earth-currents, sunspots, cosmic rays, and communication over the radio, telephone, and telegraph.

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EARTH-MAGNETIC ANALYSIS OF THE PRIMARY COSMIC RADIATION

Thomas H. Johnson

The Earth constitutes a huge magnetic spectrograph which resolves the primary, electrically-charged cosmic rays into a series of band edges, the positions of which depend upon the magnetic rigidity ($H\rho = mv/e$). The rays are deflected in vacuous space before they have become confused with the atmospheric secondaries, and the analysis is made from measurements of the intensity

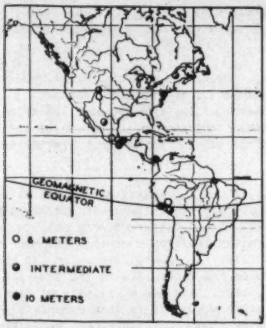

FIG. 1—MAP SHOWING EXTENT OF SURVEY OF DIRECTIONAL DISTRIBUTIONS OF COSMIC RADIATION

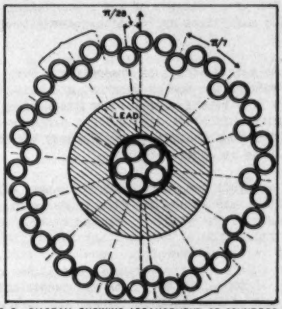

FIG. 2—DIAGRAM SHOWING ARRANGEMENT OF COUNTERS IN APPARATUS FOR DETERMINING DIRECTIONAL DISTRIBUTIONS OF COSMIC RADIATION (DOT-DASH LINES INDICATE THE DIRECTIONS OF THE VARIOUS COINCIDENCE TRAINS)

of the radiation as a function of the latitude and direction. Variations of intensity from a particular direction with respect to latitude give the distribution with respect to rigidity of the sum of the positively and negatively charged components, and the variations at a particular latitude with respect to meridian-angle give the distribution of the excess radiation of one sign of charge unbalanced by the other. Combining the two sets of experimental data it is thus possible to determine the distribution of rays of each sign of charge individually. Analysis of this type determines only the magnetic rigidity and it is necessary to invoke other methods for determining the mass, charge, and velocity individually. In the usual mass-spectrograph an electric field supplements the magnetic field and enables the determination of e/m independently of v, but in the case of the earth-magnetic analysis of the cosmic radiation atmospheric absorption must be relied upon to give the additional information. The complete analysis thus requires measurements of the intensity as function of direction, latitude, and elevation.

In 1934 measurements of the directional distributions were reported from several stations in equatorial, intermediate, and high latitudes, made with sufficient accuracy to bring out some of the principal features of the east-west asymmetry (Trans. Amer. Geophys. Union, 15th Annual Meeting, pp. 143-147, 1934; Phys. Rev., v. 45 pp. 569-585, 1934). When those measurements were analyzed in terms of the theory of the positions of the band edges, it became evident that within the limits of accuracy the positive radiation alone was sufficient to account for all of the variations of intensity with latitude. Thus there was no need to invoke any negative radiation. During the past year progress has been made by Lemaitre, Vallarta, and Bouchaert (Phys. Rev., v. 47, pp. 434-436, 1935) in developing a more accurate theory, and more extensive and accurate measurements have been realized of the angular distribution of the radiation in the important range of latitudes from 29° to 50° where most of the variations of intensity with respect to latitude take place.

The present extent of the asymmetry survey is indicated by the map of Figure 1, the stations being represented by dots. The work in 1933 resulted in reasonably accurate values of the east-west asymmetry at two stations on the geomagnetic equator at depths below the top of the homogeneous atmosphere of 6 and 6.8 meters of equivalent water, at one station in geomagnetic latitude 20° at 10.3 meters' depth, and at one station in geomagnetic latitude 50° at 10.3 meters' depth. Less accurate determinations of the east-west asymmetry were also realized at one station on the equator at 10.3 meters' depth and at three stations at 29° ranging in depth from 7.3 to 10.3 meters. During the summer and fall of 1934 extensive measurements have been realized at four other Mexican stations and at three stations in the United States. Accurate data of the east-west asymmetry were obtained in geomagnetic latitude 29° at atmospheric depths of 10.3 and 6 meters of equivalent water, in latitude 36° at a depth of 8.5 meters, and in geomagnetic latitude 50° at depths of 6 meters, 7.1 meters, and 10.3 meters. Additional studies of the north-south asymmetry were made in latitude 29° confirming some of the newer refinements of the theory of Lemaitre, Vallarta, and Bouchaert. Considerable attention has also been given to the intensity of showers both as a function of latitude, direction, and elevation, and the results have brought to light some interesting properties of this component of the radiation, which seem to have important bearing on the final analysis of the primary radiation. Studies have also been made of the effect on the east-west asymmetry of the introduction of lead absorbing-screens between the

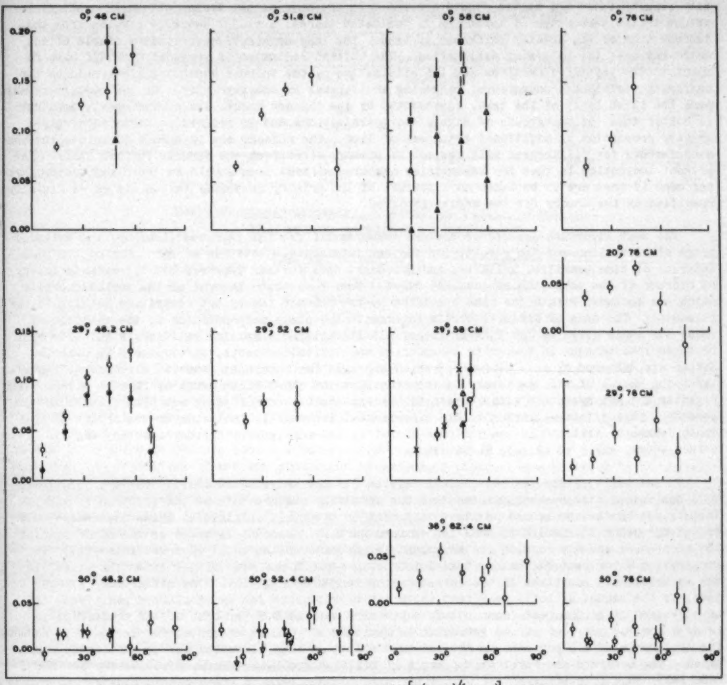

FIG. 3—SUMMARY OF ASYMMETRY MEASUREMENTS—PLOTS OF $\left[2(I_W - I_E)/(I_W + I_E)\right]$ AGAINST ZENITH-ANGLE
[NUMBERS AT TOP OF EACH PLOT INDICATE GEOMAGNETIC LATITUDE AND BAROMETRIC PRESSURE, RESPECTIVELY]

LEGEND

JOHNSON: ○=NO LEAD; ⊖=3.8 CM LEAD; ⊕=8.6 CM LEAD
ROSSI: □=NO LEAD ($\lambda=1\overline{C}^{5}$); ⊟=1.6 CM LEAD ($\lambda=1\overline{C}^{5}$)
KORFF: △=NO LEAD; ▲=30 CM LEAD ABOVE COUNTERS
STEARNS AND FROMAN: • STEVENSON: • EHMERT: ▽ ALVAREZ AND COMPTON: X

counters, for it is thought that the results of this experiment indicate in what way the measured east-west asymmetries should be corrected to account for scattering.

The apparatus used in the recent work is represented diagrammatically in Figure 2. Forty-two small counters, connected in parallel groups of three each are arranged on the periphery of a cylindrical chassis and the pulses from diametrically opposite groups are combined with those from a central group of five counters for the selection and recording of the coincidences. The instrument thus combines in one unit seven coincidence-trains, each pointing in a different direction. Automatic changes of position at regular intervals bring each counter-train successively into all of the possible directions and, without calibration as to relative sensitivities or reliance upon long time constancy, comparisons of intensities from all directions can be made. The readings are also recorded automatically.

Figure 3 presents a compilation of all of the east-west comparisons. For each station the ratio of the difference to the average of the west and east intensities is plotted against zenith-angle and the plots are arranged in the order of the geomagnetic latitude and the elevations of the corresponding stations. The principal measurements were made without additional absorbing material but lead blocks of 3.8 cm and 9 cm were also introduced between the counters

with results indicated by the shaded circles. In the case of the lesser thickness a slight increase in the percentage of asymmetry is indicated whereas a slight decrease results from the introduction of the greater thickness of lead. The lead apparently exercises a double effect which may have the following explanation. The softest radiation is somewhat diffused with respect to the primary directions and its elimination by the thinner absorbing block reduces the uniformly distributed background, producing an increase in the asymmetry. Of the radiations which pass the first layer of the lead, represented by the thinner block, the asymmetrical component is softer than the background of higher energy-radiations and is reduced in correspondingly greater proportion by additional thickness of lead. The effects are important in correcting the measurements for diffuseness with respect to primary directions and deserve further study. The present indication is that the asymmetries measured without lead should be increased two or three per cent if they are to be taken as a measure of the primary intensity in the limits of rigidity specified by the theory for the angles involved.

The most important aspects of the new measurements are the improved accuracy, the extended range of elevations, and the results for the new intermediate latitude of 36°. During the same interval of time Lemaitre, Vallarta, and Bouchaert have further improved the approximate theory of Störmer of the positions of the band edges. They have taken account of the periodic orbits which are included within the cone specified by the Störmer theory but contribute nothing to the intensity. The cone of infinite orbits intersects the plane perpendicular to the meridian at about the angle given by the Störmer theory but it includes a smaller solid angle and this must be taken into account in comparing asymmetries and latitude-effects, particularly in case the latter are measured by an electroscope which averages the intensity from all directions. An interesting aspect of the new theory is the fact that the cones illuminated by rays of a particular rigidity are not symmetric with respect to the east-west vertical plane but skew towards the equator. This effect was brought into experimental evidence by the measurements of the north-south asymmetry realized in the latitude of 29° at two atmospheric depths, 6 meters and 7.3 meters (Phys. Rev., v. 47, pp. 91-92, 1935).

On the basis of the new theoretical results for the range of latitudes from the equator to 20°, new values have been calculated from the asymmetry measurements of the fraction of the intensity due to the unbalanced positive component in the range of rigidity below that which cuts off at 60° below the zenith towards the eastern horizon. Account is taken of the absorption of the atmosphere and the results are expressed in per cent of the total observed intensity. At sea-level 4.9 per cent of the equatorial intensity and 6.3 per cent of the intensity at 20° is due to unbalanced positives in the corresponding ranges of rigidity. The difference, 1.4 per cent, is the amount of latitude-effect which can be accounted for by unbalanced positives. At an elevation of 14,000 feet (atmospheric depth of 6 meters) 6.8 per cent of the equatorial intensity and 8.8 per cent of the intensity in latitude 20° can be accounted for in the same manner. The difference of 2.0 per cent is the latitude-effect at this elevation due to unbalanced positives. The accurate sea-level measurements of Millikan and Neher (Phys. Rev., v. 47, pp. 205-208, 1935) show a latitude-effect of 0.5 per cent between Peru on the magnetic equator and Panama at latitude 20° so that practically all of the sea-level effect is to be accounted for by positives alone. At an atmospheric depth of six meters the airplane measurements of Bowen, Millikan, and Neher (Phys. Rev., v. 46, pp. 641-652, 1934) show that the latitude-effect for the same range of latitudes is also very small, possibly not exceeding the 1.5 per cent attributable to the positive component, though the accuracy is not great enough to exclude a small negative component.

In the lower range of energies, corresponding to the magnetically deviable rays in higher latitudes, the measurements are ready for an extension of the same type of analysis awaiting the development of the theory of the cut-off angles. Without the theory the latitude-effect gives a lower limit for the corpuscular component and the asymmetries show that most of the rays within the observable energy-limits are positive. The asymmetry at the equator can also be used to extend the lower limit set by the latitude-effect. Thus at an elevation of 4300 meters in high latitudes the 25 per cent corpuscular component found from the latitude-effect can be augmented by another 5 per cent because of the asymmetry found at the equator, so that at least 30 per cent of the intensity at high latitudes is definitely corpuscular. In the same way at sea-level it is found that at least 17 per cent is corpuscular. Due to the relative softness of the magnetically deviable rays, they occur in greater proportion in the direction of the vertical. From this direction 43 per cent of the high-latitude intensity at 4300 meters is definitely corpuscular.

Recent studies of shower intensities (Phys. Rev., v. 47, pp. 318-319, 1935) have also thrown a new light on the composition of the primary radiation. Table 1 gives the intensities of showers relative to the total vertical intensities (J_S/J_V) at a series of stations distributed in latitude and elevation. The constancy of the ratio with respect to changes of latitude show that the

Table 1--Comparison of shower and vertical intensities

Station	Geomagnetic latitude	Elevation	I_S Shower-intensity	I_V Vertical intensity	I_S/I_V
	°	meters	counts/min	counts/min	
Swarthmore, Pa.	50	100	2.2	12.9	0.17
Vera Cruz, Mex.	28	20	2.3	11.9	0.19
Mt. Evans, Colo.	50	4300	15.0	36.8	0.41
Nevado de Toluca, Mex.	29	4300	11.4	28.2	0.40
Copilco, Mex.	29	2280	7.4	22.8	0.32
Parral, Mex.	36	1730	4.6	17.5	0.26

Table 2--Shower asymmetry on Nevado de Toluca, elevation 4300 meters, geomagnetic latitude 29°

Zenith-angle	Average intensity $(I_W + I_E)/2$	Asymmetry $2(I_W - I_E)/(I_W + I_E)$
°	counts/min	
35	3.70	0.0122 ± 0.0114
49	2.50	0.0180 ± 0.0104

showers have about the same latitude-effect as the vertical rays and they are therefore produced by an electrically-charged component of the primary radiation. Studies of the asymmetry of the shower-particles presented in Table 2 were made at 4300 meters' elevation in latitude 29° and it was found that the ratio of the difference to the average of the east and west intensities at two different zenith-angles was very low compared with the asymmetries found for the total radiation so that we are led to believe that the shower-producing primaries consist of equal numbers of positives and negatives. Since the production of secondary photons, now believed to be an essential part of the shower-phenomenon, can be best understood from the theoretical point of view if the primaries are electrons, the combined evidence would seem to indicate that primary positrons and negatrons are also present in the cosmic radiation. It would seem to follow then that the positive asymmetrical component consists of primary protons. Its absorption-coefficient seems to be definitely less than that of the shower-producing radiation so that positive electrons can be eliminated. The heavier positive nuclei are also unlikely candidates because of the low penetrations expected of the higher nuclear charges.

The rate of absorption of radiation included within rather narrow limits of rigidity can be determined from the variation of asymmetry with zenith-angle and elevation. Data of this kind constitute a potential method for analysis of the type of particle involved if it can be shown independently, by theory or experiment, how different types of particles should be absorbed. In the case of the three latitudes 0°, 29°, and 50° the variations of asymmetry with zenith-angle and elevation are given approximately by absorption-coefficients for the magnetically deviable rays of 0.33, 0.36, and 0.53 per meter of water, respectively. The average energy of the asymmetric bands at the same three latitudes are 15, 10, and 3×10^9 volts, respectively. It is a striking fact that the absorption-coefficients vary definitely less than would be indicated by the ratio of the energies. However, we are not as yet in position to apply this finding to the problem of the nature of the primary radiation.

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THE ELECTRICITY OF RAIN AND THUNDERSTORMS

Ross Gunn

(Abstract)

It is shown that the observed properties of rain-drops of very different histories are readily described if each water-droplet and the surrounding ionized water-vapor are considered an electrical concentration-cell. The potential difference between the drop and points several radii outside approximate 0.06 volt. The equilibrium-charge on each droplet is proportional to the radius and is positive if the droplet is evaporating and negative if it is condensing. These droplets grow by association into large rain-drops and thus build up large charges of the order of 1/50 e.s.u. which discharge by conduction in a time of the order of 10^3 seconds. The

drops thereafter take on an equilibrium-charge depending upon the evaporation or condensation of the drop and its size. The calculated charges are in agreement with observation. A laboratory experiment verifying certain aspects of the predicted effects is described.

It is shown that in the presence of a rapidly rising current of air and the formation of rain-drops greater than a critical size, separation of charge takes place. At levels of condensation the atmospheric ions (usually positive) are swept to great heights while the newly-formed rain (usually negative initially) falls. Both charge-distributions discharge by conduction at different rates, leaving the charge in the zone of rain-formation in excess (usually negative). The excess charge induces charges on the Earth or on the high conducting atmosphere of a magnitude equal to a large fraction of the excess charge. Rain-drops formed by the association of droplets below the saturation-level impart a normally positive space-charge to the region. The charge-distribution resulting from the separation is quantitatively calculated from physical data and agreement obtained with observation in regard to the potential differences, electrical field, electric moment, charging current, recovery-time, and the average charge on the precipitated rain.

Some objections to Wilson's thunderstorm-theory of the maintenance are noted. It is shown that special thunderstorm-conditions in mountainous regions are such that a total storm-area of 0.01 per cent of the Earth's surface would precipitate sufficient negative charge on rain and transfer enough positive charge upward by convection to maintain the field. The possible importance of forced vertical convection over natural barriers in "fair-weather" regions is considered and it is shown that such a systematic convection may account for an appreciable part of the necessary replenishing current.

The factors determining the free space-charge are considered and the resulting distribution of charge, electric field-intensity, and potential are found.

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AN ATTEMPT TO LOCATE THE BOUNDARIES OF THE DURHAM TRIASSIC BASIN WITH A MAGNETOMETER

W. R. Johnson, Jr., and H. W. Straley, III

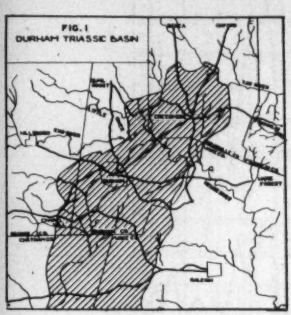
This survey was undertaken to establish the practicability of determining, entirely on the basis of variations in the Earth's magnetic field, the boundaries of a sedimentary series surrounded by igneous and metamorphic rocks. It was hoped that the difference in magnetic permeability between the various kinds of rocks was such that boundary determinations could be made with sufficient accuracy for most geological purposes. The Durham Triassic Basin (see Fig. 1) appeared to be admirably adapted to such a study.

The geology of the area has been described by Prouty (Amer. J. Sci., v. 21, pp. 473-490, 1931) and others. The sedimentary rocks are arkosic sandstones, clays, conglomerates, fanglomerates, etc., cut by mafic dikes and sills, the latter particularly concentrated in the northwestern half of the basin. The sediments were derived from the igneous and metamorphic rocks directly to the northwest and southeast. The depth to the crystalline basement is more than 500 meters at Durham.

On the southeast the Basin is terminated by a series of normal step faults, while the Triassic usually feathers out on older rocks to the northwest, although minor faults have been discovered at a number of localities. The general regional dip is toward the southeast, with numerous local reversals. Southward the Triassic sediments pass under the Cretaceous and the outlines of the Basin are concealed.

Magnetic survey--The writers made six traverses across the Basin with geomagnetic observations at half-mile intervals along the highways, distance being measured by an automobile speedometer. Magnetic observations were made with an Askania-Schmidt vertical field-balance. The reading taken over a United States Coast and Geodetic Survey bench-mark in the Arbouritum at the University of North Carolina, Chapel Hill, was taken as a base and assigned an arbitrary anomaly of zero.

The writers are indebted to J. A. Alexander, P. P. Fox, Charles Hunter, and G. R. MacCarthy



for the seventh traverse (Fig. 8). Twice G. R. MacCarthy accompanied them in the field, and on numerous occasions advised as to interpretations, etc. W. F. Prouty gave time freely for consultation on the geology. G. E. Murray assisted with the drafting.

Profiles--In the figures the abscissa represents distance, with numerals indicating stations; ordinates are in gammas. The upper curve shows directly the anomaly at each station, while in the lower the difference between successive anomalies is plotted as ordinate.

In Figure 2 the decided change in the amplitude of oscillation at station 9 appears to indicate faulting on the northwestern margin of the Basin, but there is little evidence of a similar nature to the eastward. However, the writers found faults trending sub-parallel to the Basin, but within the crystalline massif, along Dam Creek, Wake County.

It is noteworthy that the low readings of this and other traverses correlate well with the position of the fanglomerates mentioned by Prouty (loc. cit.). These low readings continue into the crystalline belt, which has been found to be extremely quartzose from the Neuse River southward toward Raleigh. The high quartz-content of these rocks is believed to bear a causal relationship to the low magnetic readings south of Neuse River.

Figure 3 represents the traverse from near Pittsboro to Raleigh. Normally one would expect heavy ferromagnesian mineral fragments removed from a disintegrating land-mass to be deposited near the margins of the basin of sedimentation. If the Basin were otherwise unaffected, a plotted magnetic traverse across it should yield a saucer-like curve. Toward the east this type of curve is closely approximated, but to the westward irregularities become the rule.

Definite inliers of crystalline rock are found along the northwestern border and these indicate that the floor of the Basin is not uniform. This factor complicates the delineation of the boundaries by any method dependent solely upon subsurface effects. The writers attribute many of the irregularities near the northwestern margin to buried topography, although it is probable that a number are due to intrusions not observed at the surface. An example of the effect of an intrusion is seen at station 18.

The traverse of Figure 4 is unique in that it does not cross the Basin from west to east, but follows almost along the strike from Durham through the middle of the trough, which is terminated by a fault on the northeast. Prouty (loc. cit.) mentions the presence of a conspicuous

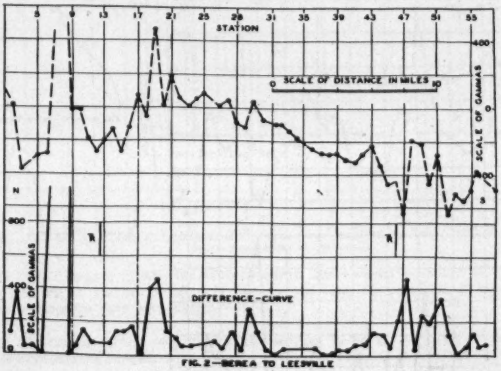


FIG. 2—SENEA TO LEESVILLE

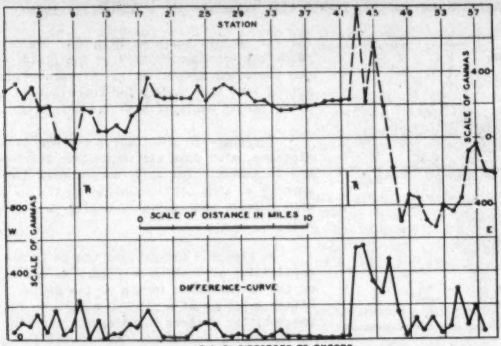
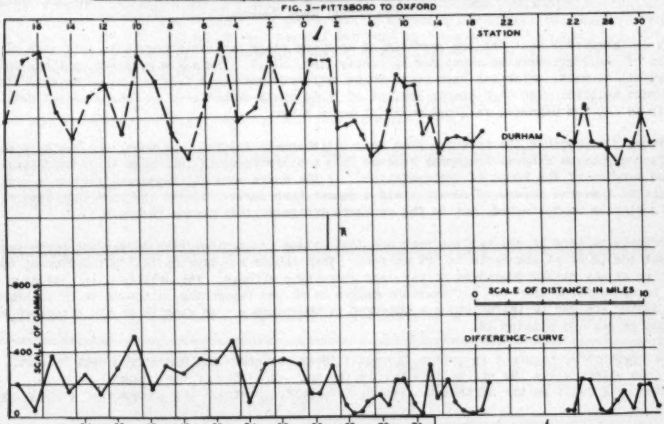


FIG. 3—PITTSBORO TO OXFORD



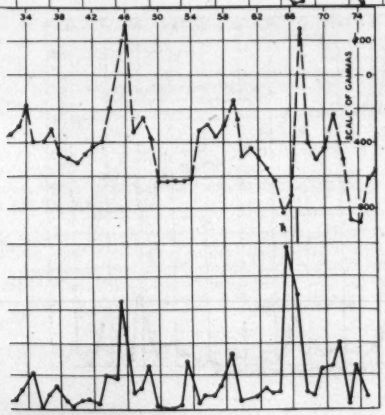


FIG. 4—HAW CREEK TO OXFORD

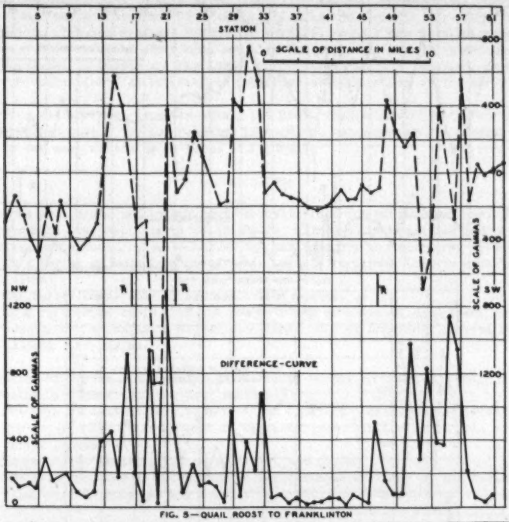


FIG. 5—QUAIL ROOST TO FRANKLINTON

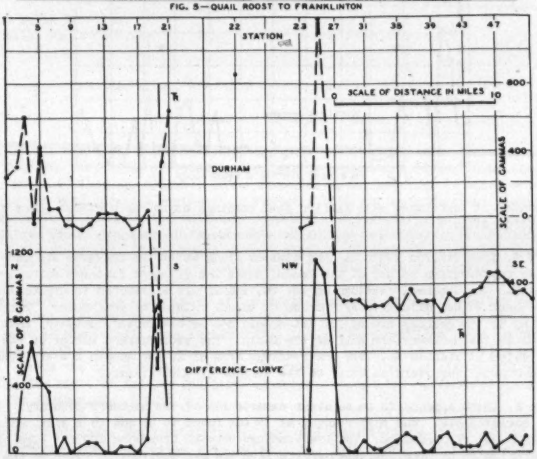


FIG. 6—QUAIL ROOST TO LEESVILLE

quartz vein 100 to 700 meters within the eastern margin and roughly parallel to the border fault. The marked low reading at station 65 appears to coincide with the position of this vein. The geologic evidence supports this conclusion.

The marked uniformity of the secondary high readings is worthy of note. These may represent dikes or buried crystalline ridges. The particularly high reading at station 46 is excluded from

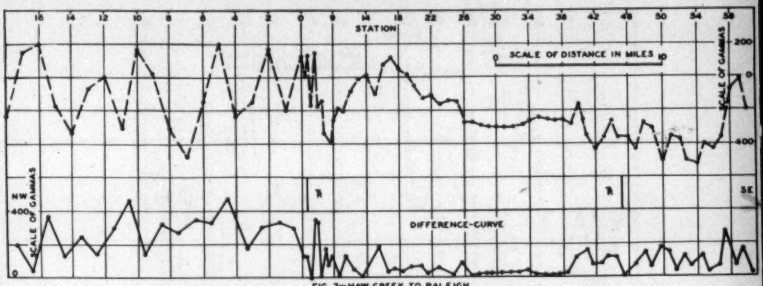


FIG. 7—HAW CREEK TO RALEIGH

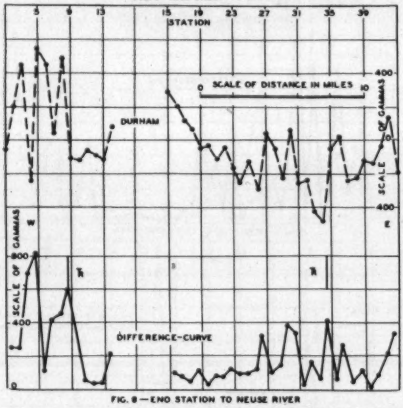


FIG. 8—ENO STATION TO NEUSE RIVER

this group because it correlates with similar peak readings on nearby highways where the writers discovered a large sill.

In Figure 5, from station 17 to 21, the highway along which the traverse was made is subparallel to the northwestern border of the Basin, where the Triassic feathers out upon the crystalline basement. The abnormal readings at 19, 20, and 21 are attributed to crystalline inliers, which may have been either uncovered by erosion or actual islands or peninsulas. This conclusion is substantiated by the geology around 19. It should not be overlooked, however, that intrusions are more common in the northwestern half of the Basin. The southeastern border of the Basin is found to be faulted at station 46. The low readings from 33 to the margin are explained by the presence of quartzose fanglomerates close to the surface in that vicinity.

In Figure 6, there appears to be no clear demarcation of the northern boundary, but the contact at 45 is unmistakable. The high reading at 19 was found to be due to a sill, which is found on three highways out of Creedmore. The low readings between Creedmore and the edge of the Basin may be attributed to fanglomerates derived from the extremely salic rocks to the south. These low readings continue into the quartzose crystalline complex itself, and are explained by the low magnetic permeability of quartz.

In Figure 7 the regularity of the readings from near Durham to station 6 is in marked contrast to the irregularity of the crystalline rocks elsewhere.

The extremely low readings southeast of Durham are explained by the fanglomerates which at-

tain their maximum development in this area. Their low magnetic permeability undoubtedly arises from the fact that they are composed of fragments of granites, low in ferromagnesian minerals and high in quartz. The low readings within the crystalline belt can be attributed to the fact that these rocks, the source of sediments, are high in quartz and low in ferromagnesia. Although the readings southeast of Durham are the lowest consecutive readings recorded, it is possible to locate the border fault from the increase in amplitude of oscillation in the curve.

In Figure 8, the curve is smoother within the Basin than without but the border is not easily located on either side. The low readings both in the basin and in the crystalline rocks can be explained by the same reasoning as those in Figure 7.

Conclusions

(1) Were the area under sufficient cover to obliterate the surface geology, it would be impossible to determine the exact limits of the Basin, although its existence could be hypothecated.
- (a) Only where faulting has occurred can the boundary be determined with certainty.
- (b) In a region of much igneous activity, mafic intrusions lead to uncertain interpretations.
- (c) The buried topography is a complicating factor.
- (d) In a restricted basin with the source-rocks so close at hand there is little opportunity for segregation of the more femic mineral fragments removed from the adjacent land-masses.

(2) Northeast of Durham the magnetic permeability of the northwestern half of the Basin appears to be uniformly higher than the southeastern.
- (a) The area of maximum development of the fanglomerates is in the southeastern part.
- (b) The crystalline rocks from which these sediments have been derived are of low magnetic permeability.
- (c) There may be faulting in the middle of the Basin.
- (d) The preponderance of intrusions in the northwestern half of the Basin supports faulting, although it may account completely for the apparent high permeability.

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SOME MAGNETIC GRADIOMETER DEVELOPMENTS DURING 1934-35

Irwin Roman and Thomas C. Sermon

In a paper (I. Roman and T. C. Sermon, A magnetic gradiometer, Amer. Inst. Min. Metall. Eng., Tech. Pub. No. 542, 1934; included in Geophysical prospecting, 1934, Trans. Amer. Inst. Min. Metall. Eng., v. 110, pp. 373-387, 1934) presented at the meetings of the American Institute of Mining and Metallurgical Engineers in February 1934, an instrument was described for measuring the ratio of the magnetic intensity-components at two nearby points. This instrument has been modified to utilize several improvements which have not required the replacement of the gradiometer-coils and frame. The purpose of this paper is to describe these improvements and to review the previous paper as much as may be required for this primary purpose.

The instrument consists essentially of two earth-inductors as nearly similar as possible and mounted in such a manner that they rotate about parallel axes and always remain in parallel planes. In each of these coils, the instantaneous induced electromotive force is proportional to the average magnetic intensity-component perpendicular to the axis of rotation and the speed of rotation. Since the coils rotate together the ratio of the induced electromotive forces will be the same as the ratio of the two intensity-components except for differences in the two inductors and for instrumental errors.

The present instrument was constructed to test the possibilities of the method without regard to refinements which might delay its construction. Accordingly, materials were selected from those available in the shops and laboratories of the Michigan College of Mining and Technology and local foundries. The same remarks apply to the modifications.

Field-tests made during the summer of 1933 indicated that the instrument could be relied upon to give a definite response which varied in a plausible manner from point to point. Further tests made during the summer of 1934 showed that at the same point and with the same orientations the readings of the previous year could be duplicated with gratifying accuracy. However, the

work of the past summer recalled Max Mason's remark (see Geophysical exploration for ores, Geophysical Prospecting, 1929, Amer. Inst. Min. Metall. Eng., pp. 9-36, 1929; paper presented at New York, October 1927), "This interpretation of the ore body's message is perhaps the most difficult part of the problem." Because of the magnitudes involved, there was considerable doubt as to whether two neighboring inductors would record a measurable difference. Now that this question seems to have been answered in the affirmative, we can attack the more involved question, "Can the records be translated into geological anomalies with sufficient reliability?" A definite answer to this question must await further study. Much remains to be done, but the instrument seems to be consistent and reasonably free of personal errors of observation.

The gradiometer in its present state is shown in Figure 1.

Circuit--Since it did not seem feasible to make field-measurements of the separate electromotive forces with the precision necessary for comparing them, a special circuit was devised to measure their ratio, which is independent of the speeds of rotation of the inductors. This circuit, shown diagrammatically in Figure 2, consists of a Kirchhoff net in the form of a complete quadrilateral as in the Wheatstone-bridge circuit. The inductors are in adjacent sides of the net, and the galvanometer is in the bridge joining the separated ends of that pair. The second diagonal of the quadrilateral consists of a wire of low resistance, while the other two sides consist of fixed resistances.

From the circuit diagram, it will be evident that the equations of the circuit are

$$\text{At B: } i_3 = i_1 + i_g \qquad \text{At C: } i_2 = i_4 + i_g$$

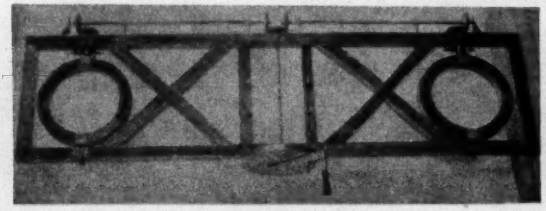

FIG. 1—MAGNETIC GRADIOMETER

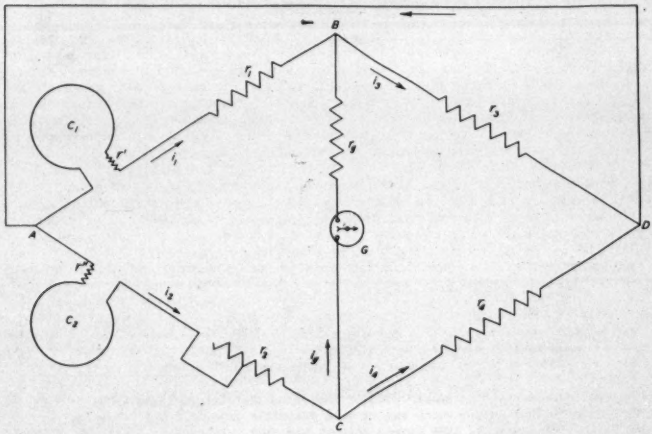

FIG. 2—DIAGRAMMATIC CIRCUIT

Through ABDA: $e_1 = i_1 r_1 + i_1 r' + i_3 r_3$ Through ACDA: $e_2 = i_2 r_2 + i_2 r'' + i_4 r_4$

Through CBDC: $i_4 r_4 = i_g r_g + i_3 r_3$

Solving these equations we find that the current through the galvanometer is

$$i_g = (a_2 e_2 - a_1 e_1)/J$$

where

$$a_1 = r_3/(r_1 + r' + r_3) \qquad a_2 = r_4/(r_2 + r'' + r_4)$$

$$J = r_g + a_1(r_1 + r') + a_2(r_2 + r'')$$

Hence, further,

$$e_2 = (a_1 e_1/a_2) + (J i_g/a_2)$$

The first term shows the value of e_2 to balance a value e_1, while the second term is the increase from the balance-value which is necessary to cause a current i_g to flow through the galvanometer. It measures the tolerance in e_2 when the circuit is balanced experimentally.

For a perfect balance, the ratio of the two electromotive forces is

$$e_2/e_1 = r_3(r_2 + r'' + r_4)/r_4(r_1 + r' + r_3)$$

In practice, it is necessary to measure the ratio integrated over the entire cycle.

Present instrument--The present instrument, a photograph of which is shown in Figure 1, consists of a frame of oak about 5-1/2 feet long and 18 inches wide. This framework is braced to carry the two inductors and the mechanical connections for maintaining the coils parallel. The coils, driven by a common shaft, are mounted to rotate accurately about axes at right-angles to the length of the frame and 4 feet apart. The coil-frames are of oak, the inner diameters being about 9 inches and the outer about 12 inches, and the wire-groove being about an inch wide and half an inch deep. The two coils were made as nearly alike as possible, each having 375 turns of No. 22 copper wire, cotton-covered, and paraffined. After winding, each coil was coated with a solution of celluloid in acetone and finally with a standard varnish to make it waterproof.

Each coil is connected to a split-ring which may be used either as a commutator or as a slip-ring by changing the positions of the bakelite cups holding the carbon brushes in the brush-blocks. The brush-blocks may be set in any azimuth around its shaft, so that direct current may be taken off as desired.

The circuit-box carries four decade-boxes and a reversing switch. Each of the two coils is connected in the circuit by means of a telephone jack mounted on the top of the box, and the galvanometer is similarly connected. The resistance r_2 consists of a four-dial box having a least count of one-tenth ohm, with its switch dials accessible on top. The resistances r_1, r_3, and r_4 consist of three-dial boxes with a least count of one ohm, mounted in the lower half of the circuit-box with their dials down and accessible through covered holes in the bottom of the circuit-box. A slip-cover protects the circuit-box when not in use and also serves as a field-table during observations, as shown in Figure 4. The reversing switch is so mounted that its bakelite rocking-arm is flush with the side of the box in neutral position.

The galvanometer is a Leeds and Northrup type 2400, with a telescope and scale. Its sensitivity is about 10^{-8} ampere per division, but by removing the scale and using a land-mark, it has been possible to detect a current of a tenth of this under favorable conditions.

To permit greater flexibility in orienting the gradiometer, a special mounting head has been constructed. This head, shown in Figure 3, consists of several parts, each fitting into and rotating with respect to its neighboring part. For definiteness, we may call these parts: (a) The base; (b) the bracket; (c) the arc; and (d) the head.

The base rests on brass cups placed over the leveling screws of a heavy tripod; it is tightened to the tripod by means of a hollow bolt which passes through a conical hole in the tripod and carries a large knurled nut pressing against the lower side of the tripod. The preliminary tightening of the base is done with this knurled nut, and the final tightening and leveling are done with the three leveling screws of the tripod.

The bracket consists of a plate carrying a shoulder riding in a socket of the base, and of two A-shaped brackets which serve to support the arc. The bracket is tightened to the base by a

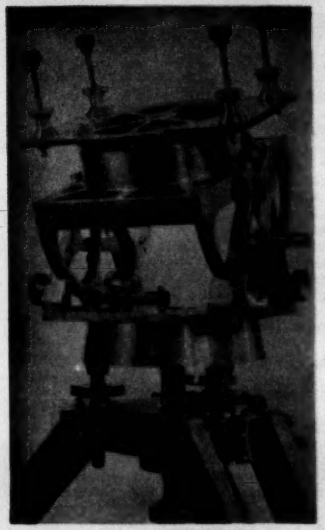

FIG. 3—MOUNTING HEAD

bolt passing through the hollow bolt of the base and pressing against the end of that bolt. The bracket has two levels mounted on the plate to permit leveling. It also has a socket and pin to receive a Brunton compass during the process of setting the arc in the proper azimuth. Suitable stops prevent the arc from turning far enough to cause damage to the levels. At the bottom of each leg of the side-supports there is a friction-clamp to hold the arc in position.

The arc rotates in a pair of bearings in the bracket so that the axis of rotation is parallel to the base of the bracket. It consists of two vertical arcs and a connecting plate. This plate may be set at any desired inclination as indicated by graduations on one of the vertical arms, and tightened to the bracket by four friction-clamps mentioned above. A slow-motion screw permits finer adjustments of the inclination of the arc-plate with respect to the bracket-plate.

The head has a shoulder riding in a socket of the arc-plate and is fastened thereto by means of a bolt passing through a hole of the latter and engaging a thread in the head. The head is free to rotate about an axis perpendicular to the axis of rotation of the arc. The head carries a short pin held in place by a flat spring. This pin engages one of four holes in the plate of the arc, so located that when the arc and head are once set in position, it is a simple matter to rotate the head through a right-angle, by lifting the pin and rotating the head until the pin drops into the next hole. The head also has four holes which engage pins fastened through the frame of the gradiometer. Each of these pins has a slot which engages a latch mounted on the lower side of the head-plate. Each has also a shoulder and a nut for fastening to the frame. These pins hold the frame of the gradiometer parallel to the head-plate.

Since experience has shown that it is inconvenient for the operator to turn the crank-handle more than five times a second, the direct drive originally used has been replaced by a planetary drive with a gear-shift. The outer (base) gear of the system is fastened to the frame of the gradiometer, while the inner (driven) gear is fastened to the main drive-shaft. Three intermediate gears each mesh with the base and inner gears and are held relatively fixed by a cover-plate which revolves with them and has sockets in which the shoulders of these intermediate gears rotate. The handle carries a key and also two pins movable perpendicularly to the plane of the gears. In slow position, one of these pins engages a hole in the driven gear, so that the handle is connected directly to the main drive-shaft. In neutral position, both pins are raised to clear the gears entirely. In fast position, the second pin is dropped to engage a hole in the center of one of the three intermediate traveling gears, making the speed-ratio about five to one; this means that the main drive-shaft rotates five times as fast as the crank-handle. A still higher ratio is contemplated by a change of the gears in the transmission-train, but at the present writing this change has not been made, and the planetary system is still in an experimental state.

Field-work--When a station-site has been selected, the tripod is set up approximately level. After the nut holding the base has been loosened, the base is leveled and clamped. The bracket is then rotated around a vertical axis until the sides of the arc are in the magnetic meridian as shown by the Brunton compass set in its socket. The axis of the arc is now horizontal and perpendicular to the magnetic meridian. Next, the gradiometer is placed on the head with the axis of rotation of the coils approximately in the direction of the magnetic intensity. One of the coils is connected directly to the galvanometer, and the inclination of the arc is adjusted until no current flows through the galvanometer when

FIG. 4—MAGNETIC GRADIOMETER AS SET UP FOR FIELD OBSERVING

the coil is rotated. This adjustment is made with the slow-motion screw and determines the direction of the intensity to within about a tenth of a degree. Then the arc is rotated through 90° so that the plane of the gradiometer-frame is perpendicular to the magnetic intensity.

Next the coils and galvanometer are connected into the circuit. (Experience has shown that the galvanometer should be a considerable distance away from the coils because of the iron in its magnets. The effect of the galvanometer varies with its orientation relative to the gradiometer; but no systematic study has been made of this effect, and the precaution of removal is the only serviceable safeguard.) As soon as the galvanometer is steady, the observer signals the operator, who turns the coils slowly with the resistance r_2 at a pre-selected value. The observer signals for a decrease or increase of r_2 as soon as he notes the motion in the galvanometer. The operator makes the indicated change and the process is repeated with increasing speeds of rotation until a balance is obtained; finally he calls the reading and the positions of the switch and coil number one to the observer for recording. The balance is then obtained with the switch reversed. The gradiometer is rotated about the magnetic intensity through a right-angle, and the observations are continued until two readings are taken for each of the four cardinal directions.

Since the observer has no knowledge of the resistance-setting and the operator no knowledge of what appears in the galvanometer, personal prejudices are negligible. In fact, interchanging observer and operator seldom changes the resulting readings. The reversing switch serves to eliminate errors in the various resistances used, as it interchanges the order in which the two coils are connected into the circuit.

The eight observations constitute a set of readings for a station and furnish the component of the gradient in the magnetic level surface. It is also possible to set the present instrument along the intensity if the dip does not exceed 78°, but this necessitates resetting of the brushes, which takes more time than seems warranted at present. If a new instrument is built, the brushes will probably be so modified that the actual vector-gradient can be measured.

A photograph of the apparatus as set up is shown in Figure 4.

Calculation of the gradient--As was shown above, the ratio of the electromotive force in series with r_2 to that in series with r_1 is

$$e_2/e_1 = r_3(r_2 + r'' + r_4)/r_4(r_1 + r' + r_3)$$

If $r_3 = r_4$ and $r_1 + r' + r_3 = M$ while $r_2 = r_1 + x$, then this ratio simplifies to

$$e_2/e_1 = 1 + (x/M)$$

In the present arrangement r_1, r_3, and r_4 have been made equal to 500, 481, and 481 ohms, respectively, while the measured resistance of each coil is 19 ohms. For this case, M is 1000.

The only component of the magnetic intensity effective in inducing an electromotive force is in a plane perpendicular to the axis of rotation of the coil. Let this component be U, and let the value of U be expanded in a Maclaurin's series with the center of the gradiometer as the origin. Then, to the first order

$$U = U_0 + z(dU/dz)_0$$

The coils may be taken as having their centers at $z = -1/2$ and $z = 1/2$, respectively, and we may assume the field sufficiently smooth so that the average intensity within each coil may be taken as that at its center. Then the ratio of the two components reduces to

$$U_2/U_1 = 1 + (1/U_0)(dU/dz)_0$$

The electromotive force developed in each coil is approximately equal to

$$e = 2\pi r^2 UwN \times 10^{-8} \text{ volt}$$

where r is the effective radius of the coil in centimeters, U is the effective field-intensity for the coil in gauss, w is the number of revolutions per second, and N is the number of turns of wire on the coil. Hence for a particular coil, we may write

$$U = Ke/w$$

where K is a constant for a particular coil. Let the coils be identified by the symbols C_1 and C_2, respectively. Let P and S denote the electromotive forces developed in those coils which are in the positions selected as principal and secondary, respectively. The principal position has usually been selected as the north or east of the two coils, and does not refer to the physical identity of the coil. Let the switch be considered as direct when coil C_1 is in series with resistance r_1 and reversed when coil C_1 is in series with resistance r_2. Let e_k be the electromotive force developed in the coil in series with resistance r_k, and V_k be the electromotive force developed in coil C_k. Let the symbols PD, PR, SD, and SR be used to indicate that coil C_1 is in the principal position when the first element is P and in the secondary position when it is S, and that the reversing switch is in the direct position when the second element is D and in the reversed position when it is R. Then for the four cases we have

$$\text{PD:} \quad P = V_1 = e_1 \quad S = V_2 = e_2 \quad P/S = e_1/e_2$$

$$\text{PR:} \quad P = V_1 = e_2 \quad S = V_2 = e_1 \quad P/S = e_2/e_1$$

$$\text{SD:} \quad P = V_2 = e_2 \quad S = V_1 = e_1 \quad P/S = e_2/e_1$$

$$\text{SR:} \quad P = V_2 = e_1 \quad S = V_1 = e_2 \quad P/S = e_1/e_2$$

As shown above, the ratio of e_2 to e_1 is x parts in M greater than unity.

If the two coils were exactly alike, the coil-constants would be equal and we could assume that the intensity-components were in the same ratio as the induced electromotive forces. In general, they can not be made exactly alike, but we may assume them so nearly alike that we may write

$$k_2 = k_1(1 + y)$$

where y is so small that powers beyond the first may be neglected. Then for the two cases PD and SR, the ratio of the intensity component at the principal coil to that at the secondary coil is

$$U_p/U_s = k_1e_1/k_2e_2 = [1/(1 + y)][M/(M + x)] = 1 - y - (x/M)$$

while for the cases PR and SD the ratio is

$$U_p/U_s = k_2e_2/k_1e_1 = (1 + y)(1 + x/M) = 1 + y + (x/M)$$

If the gradient is defined as

$$G = M(U_p/U_s - 1)$$

then we have, to the first order

$$G_{PD} = - x_{PD} - My \qquad G_{SD} = + x_{SD} + My$$

$$G_{PR} = + x_{PR} + My \qquad G_{SR} = - x_{SR} - My$$

Hence the arithmetic average of the gradient as calculated from the four observations is

$$G_o = (1/4)(x_{PR} + x_{XD} - x_{PD} - x_{SR})$$

independently of the coil-constants. It should also be noted that the speeds of rotation disappear because the two coils rotate together. Within fairly wide ranges, the gradient may be considered as independent of the temperature, to the first order of the temperature-coefficients of resistance.

Field-tests--The field-tests made since the publication of the previous paper were of two types. In the first group made at the Pilgrim River magnetic station, the chief results were to emphasize the importance of careful brush- and inclination-settings and a need for much more theoretical information than is available at present.

The second group of tests consisted in extending and checking the observations made near Trout Creek, Michigan, in 1933. The revised technique seemed to reduce the measured gradients but emphasized the reliability of the instrument in the impersonal furnishing of data. When the

gradiometer was set in the gravitational level-surface over the same stake as in the preceding year, the readings were almost identical. However, when the gradiometer was set in the magnetic level-surface, the readings were very small. One possible explanation may be that the gradient along the intensity is much larger than that perpendicular to it.

Because the new observations add nothing to our knowledge of the subject beyond what was published previously, the data are omitted. Many isolated facts of interest developed, but their interpretations are still too vague.

Problems of design--In addition to the designing of the mechanical improvements discussed above, and the field-tests made, the theoretical attack on the problem was renewed with a view to selecting the most favorable values to be used in building an entirely new instrument. Because of the complicated nature of the problem, the results are not entirely satisfactory, although several conclusions seem to be justified.

(1) It is evident that the resistances r_1 and r' will always occur together and that r_2 and r'' will likewise always occur together. Accordingly, whatever resistances are desirable in those sides of the circuit should occur largely within the coils themselves, the residues being only large enough to permit adjustment of the circuit for balance.

(2) To offset errors due to the resistances of lead wires and brush-contacts, all resistances entering the calculations should be as large as convenient for the degree of accuracy involved. The actual choice will depend to some extent on the current-detector used. Specifically, it is hoped that the Leeds and Northrup type-2400 galvanometer will be replaced by a type-2480.

(3) If the resistances r_3 and r_4 are made in the form of fixed coils while the resistances r_1 and r_2 are small, it seems quite feasible to mount the entire circuit, except the galvanometer, on the frame itself without increasing the weight unduly. This would eliminate the circuit-box and two of the three telephone-jacks.

(4) There would seem to be a number of advantages in replacing the oak frame by a frame made of channel members of some light, non-magnetic metal, possibly duralumin or Dow metal. In this case, the bearings for the various shafts could be mounted on top of the frame instead of through it, as in the present instrument. Metal work could be done more accurately than woodwork.

(5) The bearings in the present instrument were not given as much consideration as they deserve. Among the possible improvements might be included ball- or roller-bearings of some non-magnetic material or bearings made of graphite-impregnated duprene. Such bearings are still in the experimental stage, so that it is difficult to predict just how satisfactory they would be.

(6) The present coils are of large diameter with hollow centers. The same results might be obtained with smaller coils having an increased number of windings and a greater thickness. In particular, it may be desirable to use twin coils with grooves on both sides of a diametral shaft.

(7) The wire used in the present instrument is number 22 copper, cotton-covered, and paraffined. This wire was the best of several sizes available for immediate use when the coils were wound. Decreasing the diameter of the wire for a given coil-frame increases the number of turns and hence increases the induced electromotive force, but it also increases the resistance of the coil, so that there may be a best diameter to use. In any case, the low potential-differences encountered between adjoining wires and layers would seem to justify the use of enameled wire in preference to cotton-covered, and thus to reduce the insulation-space.

(8) In the present coils, the two coil-constants are not the same although they were carefully wound. To insure better uniformity, the manner of winding the coils must be controlled. Possibly some form of automatic tension-control and feed should be used. Perhaps a layer of varnish between layers will assist uniform spacing.

(9) Experience has seemed to indicate the use of direct current for the present instrument, but it is quite possible that the sensitivity of the circuit could be improved by the use of alternating current and some form of amplifier. This would eliminate the need of a commutator and the difficulties caused by brush-settings.

Conclusion--In the present paper, an attempt has been made to bring the status of the magnetic gradiometer to date. For this purpose, some material from a previous paper has been included, with such modifications as have seemed desirable. Since the publication of the previous

paper, details have been modified, and this paper discusses the revised results without specifically indicating each change. The reader interested in the developments can make the comparison for himself. It is hoped that the present paper will be complete.

The authors thank the various members of the staff of the Michigan College of Mining and Technology who have cooperated in the development of the gradiometer; in particular, they are indebted to James Fisher, Head of the Department of Mathematics and Physics, the members of the Mechanical Engineering Department, and of the shop staff.

Michigan College of Mining and Technology,
Houghton, Michigan

EARTH-POTENTIAL MEASUREMENTS MADE DURING THE INTERNATIONAL POLAR YEAR

G. C. Southworth

(Abstract)

Data are presented covering the normal diurnal variation of earth-potentials as measured at about a dozen different points, mostly in eastern United States. These data are arranged in graphical form for the convenience of the casual reader and also in numerical form for the use of the correlator. The data for Wyanet (Illinois), Houlton (Maine), and New York (New York) are based on nearly continuous recordings extending over periods of one or two years. These include the International Polar Year. At other points less extensive data were taken. These show the general characteristics peculiar to the location in question.

The data taken at Wyanet, Houlton, and New York have been analyzed for harmonic content. At New York the fundamental and to a large extent the harmonics also, are directed along a northwest-southeast line. At Wyanet and Houlton these components tend to rotate with time. The pronounced directive effect noted near New York appears to prevail rather generally along the eastern part of the United States from Massachusetts to Florida and possibly into Cuba. The rotary effect noted in the Houlton and Wyanet data is also found in data taken in the southern part of the Mississippi Valley. Most of the data point toward the generally accepted view that there is a close relation between earth-resistivity and the direction and magnitude of earth-potentials. However, there are some inconsistencies noted which tend to make this less definite.

[The complete paper will be published in the September 1935 number of the Journal of Terrestrial Magnetism and Atmospheric Electricity.]

Bell Telephone Laboratories,
New York, New York

SEASONAL VARIATION IN EARTH-CURRENTS AT TUCSON, ARIZONA

W. J. Rooney

(Abstract)

The seasonal changes in earth-current flow at Tucson (Arizona) have been determined from a study of the calm-day diurnal-variation records for the three-year period 1932-34 obtained through the cooperation of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the United States Coast and Geodetic Survey, and the American Telephone and Telegraph Company. The records are of unusual interest because of the location of Tucson in the transition-belt where the diurnal variation of magnetic dip and intensity change from high-latitude to equatorial type. The diurnal variation in earth-current potential gradient, as shown by a series of monthly hodographs, also changes radically with season. During the winter the hodographs are nearly circular with the current-vector proceeding in two clockwise loops. During the summer they are elongated greatly along a line which corresponds closely to the magnetic meridian and the clockwise rotation of the vector tends to disappear at midday. A decided parallelism with the changes noted in the diurnal variation of the magnetic elements as recorded at the same station adds to the evidence linking the two phenomena together. [The complete paper is published in the Journal of Terrestrial Magnetism and Atmospheric Electricity (v. 40, pp. 183-192, 1935).]

Department of Terrestrial Magnetism, Carnegie Institution of Washington,
Washington, D. C.

THE PURPOSE OF FURTHER ATMOSPHERIC-ELECTRIC MEASUREMENTS IN THE TROPOSPHERE AND STRATOSPHERE

O. H. Gish

Owing to the absence of the author from May to July while engaged in potential-gradient and conductivity observations at a base-station near "Strato-Camp" and in preparations for recording of atmospheric conductivity during the proposed 1935 stratosphere flight of the National Geographic Society and United States Army Air Corps from Rapid City, South Dakota, the manuscript for this paper could not be completed for publication in the Transactions. It is expected it will appear later in the Journal of Terrestrial Magnetism and Atmospheric Electricity.

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

REPORTS ON MAGNETIC AND ELECTRIC WORK OF ORGANIZATIONS IN NORTH AMERICA DURING 1934-35

Magnetic work of the Dominion Observatory, Canada

R. Meldrum Stewart

In 1930 the Dominion Observatory began a program of observations to determine the secular change of the Earth's magnetism over that part of the Dominion which, up to that time, had been covered by the survey. This was in accord with the general policy of observing periodically at repeat-stations and extending the survey to include stations in new localities. The program was continued in 1931 but was suspended during 1932 and 1933.

During the past year the work was resumed, two observers being assigned to the field. One occupied 32 stations in Alberta, British Columbia, and Yukon Territory. Of these, 24 are exact repeat-stations and the remainder, with one exception, are in the vicinity of former stations. Five of the stations in Yukon Territory were established by the Carnegie Institution of Washington in 1907. The other observer occupied 15 stations, ten of which are new and five repeat, along the route followed by the Hudson's Bay Company's steamer Nascopie during the annual cruise along the Labrador Coast, in Hudson Bay, Hudson Strait, and Eastern Arctic.

The observations in Western Canada were made with combined magnetometer-inductor No. 104, which is of the type developed by the Carnegie Institution of Washington. The instrumental equipment used by the observer on the Arctic trip included C.I.W. universal-type magnetometer and dip circle No. 20, Dover dip circle No. 212, and a compass-declinometer.

Dominion Observatory, Department of the Interior,
Ottawa, Canada

Report of the magnetic work at the Astronomical Observatory of Tacubaya during the year 1934

Joaquín Gallo

The Magnetic Station of Teoloyucan, 36 km north of Mexico City, has worked without interruption, and R. O. Sandoval has observed the absolute values twice a month with magnetometer-inductor No. 107 (C.I.W. type) and has tabulated all the data from the magnetograms of our Askania-Werke variometers.

The mean monthly values reduced to International Magnetic Standards are given in Table 1, as also the magnetic character of each month; moreover, Table 2 shows the perturbations registered during the year.

A short magnetic survey was conducted by Mr. Sandoval at the principal places around Mexico City, as shown by the values in Table 3. From this we found large local perturbations in declination at Amecameca and at Puebla. These are probably due to the volcanoes between the two cities. At Amecameca there are also local perturbations both in inclination and horizontal intensity.

Table 1--Mean monthly values of magnetic elements determined from magnetograms at Teoloyucan Observatory during 1934

Month	Declination east, D	Magnetic character	Horizontal intensity, H	Magnetic character	Vertical intensity, Z	Magnetic character	Inclination North, I
1934	° '		γ		γ		° '
January	9 35.1	0	30950	0	33319	0	47 06.6
February	9 35.0	0	31021	0	33394	0	47 06.6
March	9 36.1	0	31028	0	33402	0	47 06.6
April	9 36.6	0	30990	0	33368	0	47 06.9
May	9 36.1	0	31018	0	33361	0	47 05.1
June	9 36.1	0	31043	0	33382	0	47 04.8
July	9 35.3	0	31034	0	33417[a]	..	47 06.8[a]
August	9 36.8	0	31036	0	33415	0	47 06.8
September	9 36.6	0	31012	0	33429	0	47 08.9
October	9 35.7	0	31026	0	33492	0	47 11.3
November	9 37.3	0	31028	0	33445	0	47 08.8
December	9 36.7	0	31024	0	33422	0	47 07.8
Mean	9 36.1	..	31018	..	33403	..	47 07.3

[a]Absolute values; not meaned.

Table 2--Principal perturbations recorded at the Teoloyucan Magnetic Observatory during 1934 (times are 105° west meridian)

Date	Declination					Horizontal intensity				
	Time beginning	Duration	Maximum	Minimum	Character[a]	Time beginning	Duration	Maximum	Minimum	Character[a]
1934	h	h	° '	° '		h	h	γ	γ	
Feb. 8	....	...	.....	.....	...	17.2	13.0	31015	30994	2-F
Mar. 2	....	...	.....	.....	...	13.3	5.6	31035	30998	2
Mar. 4	21.8	6.1	9 38.3	9 35.3	2-F	10.5	38.0	31041	30982	2-FP
May 2	....	...	.....	.....	...	16.3	10.1	31031	31005	2-F
May 11	....	...	.....	.....	...	13.1	10.8	31031	30995	2-FP
May 17	....	...	.....	.....	...	18.9	7.1	31041	31023	2-F
June 11	....	...	.....	.....	...	17.1	6.1	31057	31028	2-F
July 3	3.6	4.8	9 40.3	9 33.5	2-FP	3.6	17.0	31088	31020	2-FP
July 29	....	...	.....	.....	...	20.4	10.5	31064	30995	2-F
Oct. 21	19.7	1.1	9 37.6	9 35.9	1-0	....	....	.....	.....	...
Oct. 23	20.7	7.1	9 39.5	9 32.1	1-F	20.6	7.9	31048	30971	2-F
Dec. 3	16.0	8.8	9 41.2	9 31.0	2-FP	14.8	13.4	31037	30904	2-FP
Dec. 29	....	...	.....	.....	...	9.2	14.1	31012	30930	2-FP

	Vertical intensity				
			γ	γ	
Oct. 23	0.4	3.5	33511	33423	2-F
Dec. 29	9.1	9.5	33434	38349	2-F

[a]The remarks in the "Character" columns are to be interpreted in accordance with following legend: 0 = calm; 1 = slightly disturbed; 2 = disturbed; 0 = bays; 20 = two successive bays; Od = double bay; F = fluctuations; P = pulsations.

Table 3--Results (reduced to International Magnetic Standards) of magnetic survey during 1934 in Mexico

State	Place	Latitude north	Longitude west	Date	Declination east, D	Inclination north, I	Horizontal intensity, H	Z = H tan I
		° '	° '	1934	° '	° '	γ	γ
Hidalgo	Tula	20 03.5	99 20.6	.863	8 44.5	47 18.0	31183	33794
	Tulancingo	20 04.8	99 22.3	.882	9 27.9	47 50.1	30733	33935
	Pachuca	20 07.8	98 43.8	.877	9 41.1	47 53.0	30824	34094
Mexico	Amecameca[a]	19 07.5	98 46.1	.855	8 57.4	47 37.1	30561	33490
	Toluca	19 17.6	99 40.7	.850	8 41.5	46 15.1	31117	32507
Morelos	Cuautla	18 48.4	98 57.9	.965	9 35.1	45 57.1	31290	32347
	Cuernavaca	18 59.0	99 14.3	.973	9 32.3	46 07.0	31410	32659
Puebla	Matamoros Izucar	18 36.1	98 28.2	.907	9 32.5	45 45.0	31244	32073
	Puebla[a]	19 03.2	98 11.0	.894	9 45.1	46 20.2	31303	32799
Tlaxcala	Apizaco	19 24.9	98 32.7	.900	9 25.0	46 50.5	31225	33299

[a]Local disturbance.

Observatorio Astronomico Nacional, Universidad Nacional de Mexico,
Tacubaya, D.F., Mexico

Research in atmospheric electricity at Stanford University

Joseph G. Brown

After ten years of work in atmospheric electricity in the Department of Physics at Stanford University the reporter retired as Professor Emeritus and the work is being continued under the direction of Professor Norris E. Bradbury. During the past year Professor Brown has been making an analysis of the diurnal variation of the potential gradient from all available data, and will continue his studies in this field in cooperation with the Department of Physics.

Professor Bradbury has been working for several years on gaseous ions and will now start a study of atmospheric ions with special reference to their structure and mobility.

Russell A. Nielson completed his study of dust-content of the atmosphere (Terr. Mag., v. 39, pp. 281-292, 1934) and is now working on a laboratory problem on the mobility of electrons. Mr. Williams has completed his equipment for air-earth current-measurements and is now obtaining continuous records. In connection with this problem he has devised a mechanical collector which is very rapid in its action and does away with the undesirable ionization of a rapid radioactive collector. He has also made some progress in developing a light portable equipment for potential-gradient recording on a captive-balloon.

Stanford University,
Stanford University, California

Researches at Mount Wilson Observatory of the Carnegie Institution of Washington relating to terrestrial magnetism

Seth B. Nicholson

Magnetic character-figures estimated from the records of horizontal intensity and declination, and solar character-figures from spectroheliograms have been reported regularly in the Journal of Terrestrial Magnetism and Atmospheric Electricity (v. 39, pp. 163-164, 242-243, and 351-352, 1934, and v. 40, pp. 115-116 and 218-219, 1935).

The minimum of the solar cycle occurred near the end of 1933, and since then the number of spots belonging to the old cycle has decreased, while the number in the new cycle has increased. In the six months, March to August, 1934, eight groups of the old cycle and 24 of the new cycle were observed, and in the six months September, 1934 to February, 1935, four groups of the old and 42 of the new cycle.

The activity of the Earth's magnetic field as judged by the magnetic character-figures was the same in 1933 as in 1934. The number of sunspots will certainly increase rapidly during the

next few years and more opportunities will be available for comparing solar activity and terrestrial-magnetic effects.

In connection with the cooperative spectrohelioscope-program for watching the Sun during the whole day by observations made at several stations around the world, it is planned to photograph the Sun in hydrogen light continuously for the greater part of the daylight hours at Mount Wilson in order to obtain an unbroken solar record for comparison with magnetograms.

Mount Wilson Observatory, Carnegie Institution of Washington,
Pasadena, California

IONOSPHERE-RESEARCHES OF THE NATIONAL BUREAU OF STANDARDS

J. H. Dellinger

The measurements of the critical frequencies and virtual heights of the various regions of the ionosphere have been continued with automatic recording equipment for the frequency band 2500 to 4400 kc/sec and with manually operated equipment for the frequency bands 600 to 2500 kc/sec and 4500 to 11,000 kc/sec. Certain of the results and their applications to radio wave-propagation have been published in the following papers: T. R. Gilliland, J. Res. Bur. Stan., v. 14, pp. 283-303, 1935; S. S. Kirby and E. B. Judson, J. Res. Bur. Stan., v. 14, pp. 469-486, 1935; T. R. Gilliland, Nature, v. 134, p. 379, 1934; E. B. Judson, Phys. Rev., v. 47, p. 509, 1935; S. S. Kirby, T. R. Gilliland, and E. B. Judson, Phys. Rev., v. 47, pp. 632-633, 1935.

Automatic recording equipment for the range of frequencies about 500 to 12,000 kc/sec was under construction and is expected to be in operation about the end of the year 1935.

National Bureau of Standards,
Washington, D. C.

Magnetic work of the United States Coast and Geodetic Survey, April 1934 to March 1935

R. S. Patton

Magnetic surveys--Repeat-observations for determining the secular change were made at 85 stations in 28 states, covering most of the northern half of the United States. This practically completes the data needed for bringing the results of observations up to 1935 and the preparation of magnetic charts for that date. In addition, new stations have been established and old stations have been replaced for the benefit of local surveyors, particularly in South Carolina.

Declination-observations have been made at triangulation-stations in Alaska and in the Philippines, at a number of airports to provide means for testing airplane compasses, and along the approaches to Wilmington (North Carolina), Georgetown and Charleston (South Carolina) to provide ranges for adjusting the compasses of vessels entering those ports. Some observations are being made under state auspices with instruments loaned by this Bureau.

Magnetic observations--The five magnetic observatories have been operated without serious interruption. The repairs to the Cheltenham variation-building were completed in June, 1934, and the regular instruments were restored to normal functioning beginning July 1. With the cooperation of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, its sine-galvanometer has been installed at Cheltenham and provision made for control of the temperature of the standard cells; it is expected that this instrument will be used for the regular observations of horizontal intensity as well as for instrumental comparisons.

In cooperation with the Cosmic-Ray Committee of the Carnegie Institution of Washington, a cosmic-ray recording apparatus has been installed at Cheltenham and is being operated by the Observatory personnel.

Piers have been erected at Cheltenham, Tucson, and Sitka on which to mount insensitive la Cour variometers after the completion of a series of test-comparisons at Cheltenham.

At Tucson (Arizona) it has been possible to continue the photographic recording of variations of conductivity, potential gradient, and earth-currents with the cooperation of the Carnegie Institution of Washington, the American Telephone and Telegraph Company, and the Mountain States Telephone and Telegraph Company.

Development of instruments--In cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, work is in progress having for its object the improvement of the instruments for measuring the Earth's magnetism and its variations. Particular attention is being given to the development of electrical methods in absolute observations, which it is hoped will result in accuracy, rapidity, and convenience not attained by other methods. Comparisons are being made of various types of vertical-intensity variometers with a view to eliminating certain present difficulties.

Publications--During the year it was possible to issue "Alaska magnetic tables and magnetic charts for 1930" and "Results of observations at the Tucson Magnetic Observatory in 1925 and 1926." By adopting a less expensive method of reproduction and reducing the number of copies to correspond more nearly with the number of actual users, it has been possible to continue the issue of observatory-results. Those for Cheltenham and Honolulu for 1927 and 1928 have already been distributed and those for Sitka and Tucson will be ready in the near future.

Revised editions of "Magnetic declination in Florida" and "Magnetic declination in California and Nevada," bringing the results up to 1935, have been prepared and similar publications for Alabama, Mississippi, and Georgia are in preparation.

The computation of the College-Fairbanks Polar-Year observations is now progressing rapidly, after many difficulties in determining the instrumental constants and base-line values.

Reports of magnetic character of days and of magnetic activity for the five magnetic observatories have been forwarded regularly to the International Commission for Terrestrial Magnetism and Atmospheric Electricity. The Cheltenham Observatory furnishes daily reports of magnetic character of day for the radio broadcast of cosmic data sent out under the auspices of Science Service.

U. S. Coast and Geodetic Survey,
Washington, D. C.

Researches related to terrestrial magnetism and electricity of the United States Naval Research Laboratory

H. R. Greenlee

Equipment is being developed to record automatically and continuously the directions of radio static. It is planned to install the static direction-recorders at stations several hundred miles apart in order to investigate their possibility in locating storms.

Ross Gunn has prepared a quantitative theory of the electricity of rain and thunderstorms (Terr. Mag., v. 40, pp. 79-106, 1935) which yields agreement with observation. The theory is based on the hypothesis that each droplet of water and its surrounding ionized vapor constitutes a concentration-cell of about 60 millivolts difference of potential. He has dealt with (Terr. Mag., v. 39, pp. 265-276, 1934) the origin of the Sun's electric field from the standpoint of the systematic drift of the ions of the solar atmosphere.

An analysis of recent ionosphere-observations by E. O. Hulburt led to the conclusion that the upper atmospheric ionization is caused chiefly by the ultra-violet light of the Sun. An explanation is given of the more prominent features of the E, F_1, F_2, and F-regions.

U. S. Naval Research Laboratory,
Washington, D. C.

Auroral and ionospheric station at the Alaska Agricultural College and School of Mines

Veryl R. Fuller

Auroral research--A report of work on the Aurora Borealis for the years 1932-34 conducted at the Alaska Agricultural College and School of Mines (University of Alaska from July 1, 1935) at College, Alaska, was prepared and is to be published in the September 1935 number of the Journal of Terrestrial Magnetism and Atmospheric Electricity. This report is a summary of the visual observations made during the period stated. Good progress has been made on the reductions and discussions of the auroral parallactic photographs obtained through the five-year grant of the Rockefeller Foundation. That work was concluded December 31, 1934, at the end of the

five-year period. It is hoped that funds may be secured later to continue this work; meanwhile the attempt will be made to continue visual observations on the limited scale permitted by the spare time of the reporter.

Ionospheric research--As a part of the program of ionosphere-investigation during the Second International Polar Year, stations equipped for continuous registration of ionosphere virtual-heights were located in and near Fairbanks, Alaska. Upon the completion of the Polar-Year work, it was decided to continue the investigations with the support of the Navy Department, the Signal Corps of the United States Army, the Alaska Agricultural College and School of Mines, and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. The investigations were continued during the winter of 1933-1934. Continuous automatic registrations of ionosphere virtual-heights on a frequency of 2050 kc were made. The transmitter and receiver were operated at separate locations until February 10, 1934, when they were moved to College, Alaska, and further modified for side-by-side operation. Thus with one operator step-by-step multifrequency measurements yielding values of ionic densities may be made.

After a period of adjustment and test, side-by-side operation was begun in May 1934. Very successful records have been obtained in this way, and difficulties experienced because of change of phase of the power-supply between the transmitter and the receiver have been eliminated. The character of continuous records when the equipment is assembled in one location under immediate supervision is much improved.

Recording will be discontinued for the summer at the end of May since the University's power-plant will not be operating then. Because of the importance of continued summer measurements, plans are under consideration in cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for the installation of an auxiliary power-supply and frequency-control equipment of the type used by the observatories of the Department of Terrestrial Magnetism. This will have the additional advantage of making available power at a well-controlled frequency at all times.

A partial compilation of the data obtained during the winter was made and forwarded to the Department of Terrestrial Magnetism for study. A first report was published (see J. A. Fleming, Report on ionosphere-investigations conducted at College-Fairbanks, Alaska, during the winter of 1933-34, Terr. Mag., v. 39, pp. 305-314, 1934). The tabulated values of virtual height during the morning show that, following the appearance of the critical frequency, the virtual heights fall rapidly to an average value of about 210 km, identifying the layer returning reflections on this frequency as the F-layer.

The periods during which reflections are returned and the times of critical frequency are shown. The usual morning increase in ionization is shown to be associated with sunrise, and from these data it is deduced that the ionizing rays of the Sun must be absorbed below a certain limit in the atmosphere when they are directed parallel to the surface of the Earth. The decrease in ionization in the afternoon is associated with time of sunset, but is not as regular. Reflections are observed most frequently near sunrise and sunset, indicating increased absorption near noon. E-layer reflections are seldom observed, and then only at night, indicating that the maximum ionization of the E-layer is not sufficient to prevent penetration on 2050 kc.

Comparison of the ionosphere-data and the magnetic records at the College station is made. The magnetic disturbances usually occurred at night. There was a strong tendency for the usual morning reflections to fail to appear during or following a magnetic disturbance.

[Note by Editor: Professor Fuller died suddenly May 30, 1935. Thus, the program will be interrupted until the arrival of his successor, Dr. E. H. Bramhall, recently Physicist of the Second Byrd Antarctic Expedition. He hopes to continue the researches initiated by Professor Fuller and to undertake the completion of reductions and report on accumulated parallactic auroral data.]

Alaska Agricultural College and School of Mines,
College, Alaska

Magnetic and electric investigations of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, April 1934 to March 1935

J. A. Fleming

The work of the Department since the report published in the Transactions of the Fifteenth Annual Meeting may be classified generally as follows: (1) Reduction and study of observational material already gathered; (2) development of methods and technique to obtain continuous records of the electrical conditions and their variations in the ionosphere; (3) continued attack in the laboratory on basic phenomena of magnetism through experimental work in nuclear physics; (4) maintenance of field-operations to preserve continuity of secular-variation material and of records at observatories for seasonal, diurnal, and irregular fluctuations of the Earth's magnetic and electric fields.

The analyses of time-functions in geophysical data and of the interrelations existing between them are a necessary basis for a study of the fluctuations, variously termed cycles, periodicities, or occurrences so pronounced in terrestrial magnetism and electricity. To prove the physical significance of any cycle it is generally sufficient to demonstrate that it recurs frequently enough and this consideration leads in some way or other to statistical methods and to the theory of probability. This fundamental statistical aspect has been treated in a paper on "Random fluctuations, persistence, and quasi-persistence in geophysical and cosmical periodicities." Between the two extreme cases of random fluctuations and persistent waves, hitherto discussed exclusively, the intermediate case of quasi-persistence must be introduced and recognized as a common phenomenon in time-functions of geophysics. The methods developed are flexible enough to yield a wide range of applications.

The first ionospheric data from the south temperate zone have become available with the commencement of ionospheric investigations at the Watheroo Magnetic Observatory in January 1935. Results already bear upon the obscure causes of the variation of ion-density in the highest ionospheric region. These are of particular importance because this region is directly exposed to nearly the whole range of solar radiation and should therefore give a sensitive measure of solar changes.

Advances in technique of measurement have been accomplished with the commencement of continuous automatic single-frequency recording of ionospheric changes at the Huancayo Magnetic Observatory. Installation of the recording apparatus with the associated power- and control-equipment completes the first step in the program for complete recording of ionospheric details at the observatories. A similar equipment for the Watheroo Magnetic Observatory is well advanced. Polarization-experiments at the Huancayo Magnetic Observatory show the doubly-refracted components from the ionosphere to be plane-polarized. This evidence verifies theoretical predictions and establishes Huancayo as a unique location for additional special experiments relating to the terrestrial-magnetic field because of its position on the geomagnetic equator.

Development of automatic wide-range multifrequency equipment has been well advanced. Simplifications in design on the basis of experiment make possible a rugged and reliable final design.

A study of the combined data from the Huancayo and Watheroo magnetic observatories together with data from the northern hemisphere has made possible a complete delineation of the general features of the separation of the upper ionospheric-region at small zenith-angles of the Sun.

The objective of the program in the laboratory at Washington has been the formation and investigation of basic aspects of magnetism through studies in fundamental physics. Important new results included those on the disintegration of atomic nuclei by resonance-processes and on carbon reactions relating to the mass-values of carbon and lighter atomic nuclei. The experimental technique was improved by the design and construction of a capillary-arc ion-source and by the development of vacuum-tubes operating reliably at high voltages and which focus practically the whole of the input-current which is projected into the electrode-system of the tube.

The usual schedules of observations in terrestrial magnetism and electricity have been continued at the Watheroo and Huancayo observatories, as also the reductions and discussions of the results obtained. The rapid-running la Cour magnetographs of Polar-Year type were also operated at both of these observatories throughout the year. Cooperation with the Apia Observatory was continued. With the completion of the International Polar-Year program, discussion was begun of the data obtained at College-Fairbanks (terrestrial electricity, aurora, and ionosphere), at Point Barrow (terrestrial magnetism and aurora), and at Little America (Second Byrd Antarctic Expedition--terrestrial magnetism and aurora).

Field-operations, although not on as large a scale as in previous years, were continued and were devoted primarily to obtaining data at widely-distributed stations for isoporic studies. Numerous cooperative enterprises have been undertaken. The stations occupied during the year were along the east coast of Africa, in west-central China to Tibet, in southern China, in Alaska, and in South Australia. In Antarctica, 21 field-stations were occupied during sledge-trips of the Second Byrd Antarctic Expedition; observations were obtained at Easter Island on the outward journey and at Albemarle Island of the Galapagos Group and at the Canal Zone on the return journey. The total number of repeat-stations occupied during the year was about 100.

Intercomparisons of the provisional international magnetic standards of the Department with those of various observatories were made by field-observers at every opportunity. Preliminary arrangements were made for the installation of C.I.W. sine-galvanometer No. 1, following the improvement of its current-measuring appurtenances, at the Cheltenham Magnetic Observatory upon the installation there of the necessary electrical power and additional building- and pier-equipment. Through observations already arranged for at the Abinger (England), Niemegk (Germany), and Cheltenham (United States) magnetic observatories, it is planned to obtain relations between the standards of these observatories and in particular between the standard electromagnetic instruments of Abinger, of Agincourt, and of Cheltenham.

Instrumental designs and developments have been continued. Attention is being paid to the development of an electromagnetic instrument for determining the three elements--a work begun in cooperation with the Coast and Geodetic Survey. Study of suitable principle and of design for the development of vertical-intensity variometers has been begun to replace the pivot or knife-edge types now generally used which still leave much to be desired in certainty of performance over long-periods.

As in the past year, every effort was made to stimulate interest of, and to cooperate with, other organizations and investigators in all parts of the world in every aspect of the Department's activities. Rapid progress has been made in coordinating and in cementing international relations in geophysical research.

Greater detail regarding the activities of the Department will be found in the report of the Director of the Department of Terrestrial Magnetism in Year Book 33 of the Carnegie Institution of Washington (pp. 199-246, 1934). A reprint of this report may be had upon application to the Department. A few of the papers published during the past year are listed below:

J. Bartels, Twenty-seven-day recurrences in terrestrial magnetism and solar activity during 1932-33, Terr. Mag., v. 39, 201-202, 1934.

-----, Random fluctuations, persistence, and quasi-persistence in geophysical and cosmical periodicities, Terr. Mag., v. 40, 1-60, 1935.

L. V. Berkner and H. W. Wells, Report of the ionosphere-investigations at the Huancayo Magnetic Observatory (Peru) during 1933, Proc. Inst. Radio Eng., v. 22, 1102-1123, 1934.

-----, -----, F-region ionospheric-investigations at low latitudes, Terr. Mag., v. 39, 215-230, 1934.

J. A. Fleming, The relations of magnetic and electric work in the Pacific Ocean to the Polar-Year campaign, 1932-33, Proc. Fifth Pacific Sci. Cong., Victoria and Vancouver, B. C., Canada, 1933, v. 3, 1685-1690, 1935.

-----, Report of ionosphere-investigations conducted at College-Fairbanks during the winter of 1933-34, Terr. Mag., v. 39, 305-313, 1934.

-----, The distribution and need of additional magnetic observations and secular-variation stations in the Pacific Region, Proc. Fifth Pacific Sci. Cong., Victoria and Vancouver, B.C., Canada, 1933, v. 3, 1675-1685, 1934.

J. W. Green, Magnetic secular-variation in the Pacific Region, Proc. Fifth Pacific Sci. Cong., Victoria and Vancouver, B.C., Canada, 1933, v. 3, 1669-1674, 1934.

H. D. Harradon, List of recent publications (terrestrial and cosmical magnetism, terrestrial and cosmical electricity, miscellaneous), Terr. Mag., v. 39, 166-172, 255-264, and 320, 324, 332, 350, 1934; v. 40, 227-234, 1935.

W. C. Parkinson, Problems of terrestrial electricity which further observations in the Pacific Region will help to solve, Proc. Fifth Pacific Sci. Cong., Victoria and Vancouver, B.C., Canada, 1933, v. 3, 1845-1852, 1934.

W. J. Rooney and L. K. Sherman, Earth-current measurements at the College-Fairbanks Polar-Year Station, Terr. Mag., v. 39, 187-199, 1934.

M. A. Tuve, O. Dahl, and C. M. Van Atta, Low-power positive-ion source of high sensitivity, Phys. Rev., v. 46, 1027-1028, 1934.

G. R. Wait and O. W. Torreson, Large-ion and small-ion content of air in occupied rooms, Heating, Piping, and Air-Conditioning, v. 7, 105-110, 1935.

H. W. Wells, Critical-frequency observations of the E-layer at the Huancayo Magnetic Observatory, Terr. Mag., v. 39, 209-214, 1934.
W. H. Wells, The scattering of protons on protons, Phys. Rev., 591-596, 1935.

Department of Terrestrial Magnetism,
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Washington, D. C.

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AMERICAN GEOPHYSICAL UNION

Sixteenth Annual Meeting

SECTION OF OCEANOGRAPHY

Washington, D. C.
April 28, 1935

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THE WORK OF THE HYDROGRAPHIC OFFICE OF THE UNITED STATES NAVY DURING APRIL 1934 TO APRIL 1935 IN THE FIELD OF OCEANOGRAPHY

W. R. Gherardi

In the field of oceanography the activities of the Hydrographic Office and the United States Navy during the past year continued to be varied and covered widely-separated areas. They are briefly summarized below.

United States Naval surveys--Furthering its program of accurately surveying and charting Caribbean and Central American waters, due to their increasing importance and the incompleteness and inaccuracy of existing charts, the Hydrographic Office had two Naval vessels employed under its direction during the past year as follows:

The U.S.S. Hannibal and Nokomis during the first part of the year were engaged in surveying the waters of the west coast of Panama from Naranjas Island to Burica Point, the latter on the boundary between Panama and Costa Rica (Fig. 1).

During the latter part of the year the Nokomis began a survey of the waters of the harbor of Cartagena, Colombia, and approaches, while the Hannibal continued surveying the waters on the Pacific Coast of Central America--off Panama--and started surveying the Gulf of Nicoya, Costa Rica, and approaches.

During the past year the Hannibal and the Nokomis completed surveying a total water-area of approximately three thousand square miles (nautical) in Panaman and Costa Rican waters.

Unless unforeseen difficulties present themselves the surveying operations at present contemplated by the Hydrographic Office on the Pacific Coast of Central America will be completed this year after which it is expected surveying operations will continue in the waters on the Atlantic side of Central America. The results of these surveys more than justify the Hydrographic Office policy of expediting this work as many discrepancies came to light. New charts based on these surveys, complete in every detail, will be of great value to all vessels approaching the Pacific entrance to the Panama Canal, and, in addition, will open new and shorter routes to coastal shipping. Aerial photography by the use of a five-lens camera has expedited the completion of these surveys, not only in the execution but also in the planning and preliminary study of the many problems involved.

The main triangulation of the Gulf of Panama survey, completed during the previous season, was expanded westward as far as Burica Point on the Panama-Costa Rica boundary. A check base and

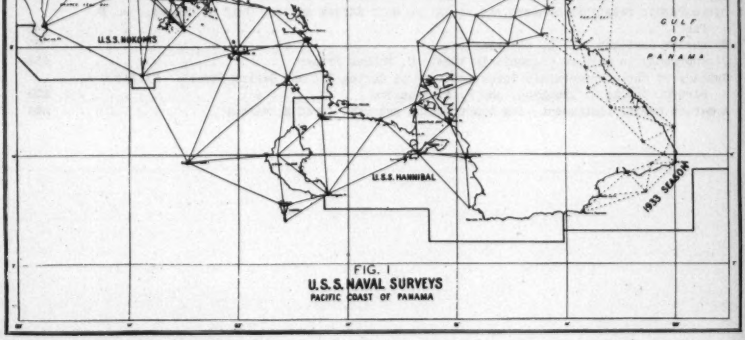


FIG. 1
U.S.S. NAVAL SURVEYS
PACIFIC COAST OF PANAMA

astronomical azimuths measured in the Parida Island area indicate a high order of the triangulation expansion over a distance of approximately 250 nautical miles (Fig. 1). Precise astronomical observations of geographic positions and determinations of the magnetic variation, horizontal intensity, and dip were made at Jicarita Island and Puerto Armuelles. After the earthquake of July 21, 1934, which caused much destruction in Ciudad de David and Puerto Armuelles, a resurvey was made of the Puerto Armuelles area which failed to disclose any material change in depths.

The U.S.S. Oglala and auxiliaries conducted surveys among some of the Aleutian Islands.

Charts from United States Naval surveys--Seven new Hydrographic Office charts were published during the calendar year of 1934 based upon original United States Naval surveys. They are: No. 1019, Gulf of Panama; No. 1060, Puntarenas and approaches, Costa Rica; No. 1884, Nipe, Levisa, and Cabonico bays, Cuba; No. 1989, Puerto Tanamo, Cuba; No. 2629, Puerto Gibara to Cayo Moa Grande, Cuba; No. 5587, Gulf of Paria, Venezuela; and No. 5618, Punta Quepos Anchorage, Costa Rica.

Echo (sonic) soundings obtained by United States Naval vessels--The following is a tabulated list of echo (sonic) soundings taken by United States Naval vessels from January 1, 1934, to December 31, 1934:

U.S.S. Nokomis - 64 sonic soundings obtained en route San Salvador to Cape Maysi, Cuba, crossing 17° 45' 20" N in 74° 51' W, 13° 28' N in 77° 40' W, and 8° 16' 20" N in 82° 52' 15" W.

U.S.S. Hannibal - 607 sonic soundings taken in North Atlantic, Caribbean Sea, Panama Bay, and off coast of Central America, crossing 36° 56' 45" N in 75° 54' 30" W, 20° 11' 30" N in 74° 04' 15" W, 7° 31' 30" N in 81° 14' 30" W, and 9° 14' 15" N in 84° 25' 30" W.

U.S.S. New Mexico - Line of 22 fathometer-soundings taken in Port au Prince Bay and St. Mare Channel, Haiti, in 18° 40' N and 72° 40' W.

U.S.S. Bridge - 47 sonic soundings in Santaren Channel, crossing 23° 23' N in 79° 14' W.

U.S.S. Holland - Line of 40 sonic soundings in North Pacific, crossing 9° 36' 15" N in 87° 54' 45" W.

U.S.S. New Orleans - 43 sonic soundings in North Atlantic, crossing 41° 24' N in 45° 27' W, and 58° 40' 30" N in 8° 25' W.

U.S.S. Bonita - 14 sonic soundings over Thetis Bank, crossing 24° 38' 30" N in 112° 28' W.

U.S.S. Sirius - 220 sonic soundings in North Pacific, crossing 48° 40' 45" N in 125° 30' W, and 54° 11' 30" N in 166° 30' W.

U.S.S. Quail Am(15) - Line of 28 sonic soundings taken in North Pacific, crossing 53° 58' 15" N in 166° 31' W, and 53° 17' N in 169° 57' W.

U.S.S. Ramapo - 438 sonic soundings taken in North Pacific, crossing 49° 12' N in 127° 05' W, 55' 35' N in 147° 02' W, and 53° 57' N in 163° 02' W.

U.S.S. San Francisco - Line of 374 sonic soundings taken en route Acapulco, Mexico, to Hilo, Territory Hawaii, crossing 16° 45' N in 100° 00' W, 15° 20' N in 127° 15' W, and 19° 45' N in 154° 51' W.

U.S.S. Sirius - Line of 24 sonic soundings taken en route Unalaska to Straits of Juan de Fuca, crossing 49° 15' N in 127° 11' 45" W, 54° 02' 30" N in 166° 16' 30" W, and 53° 51' N in 165° 25' 40" W.

U.S.S. Canopus - 58 sonic soundings obtained en route Manila, Philippine Islands, to Saigon, French Indo-China, crossing 11° 35' N in 111° 09' 50" E and 13° 18' 15" N in 116° 41' 30" E.

U.S.S. Hannibal - 11 sonic soundings taken en route to Montuosa Island, Republic of Panama, crossing 7° 30' 40" N in 82° 07' 35" W.

U.S.S. Wright - Line of 45 fathometer-soundings in Hecate Strait, British Columbia, crossing 50° 56' N in 128° 09' W.

U.S.S. Augusta - Line of 24 fathometer-soundings taken en route Tsingtao to Chefoo, China, crossing 36° 03' 57" N in 120° 44' 30" E, and 37° 11' 12" N in 122° 49' 10" E.

U.S.S. Sirius - 360 sonic soundings in North Pacific from 48° 31' 45" N and 125° 07' 30" W to Unimak Pass and return.

U.S.S. Bushnell - 740 sonic soundings taken en route Montauk Point, Long Island (New York), to Coco Solo, Canal Zone, crossing 42° 20' N in 71° 55' W, 20° 13' N in 74° 00' W, and 9° 32' N in 79° 50' W.

U.S.S. Bushnell - 211 sonic soundings taken en route Panama to San Diego, California, crossing 7° 08' N in 81° 47' 30" W, 15° 09' 00" N in 97° 34' W, and 32° 34' N in 117° 23' 00" W.

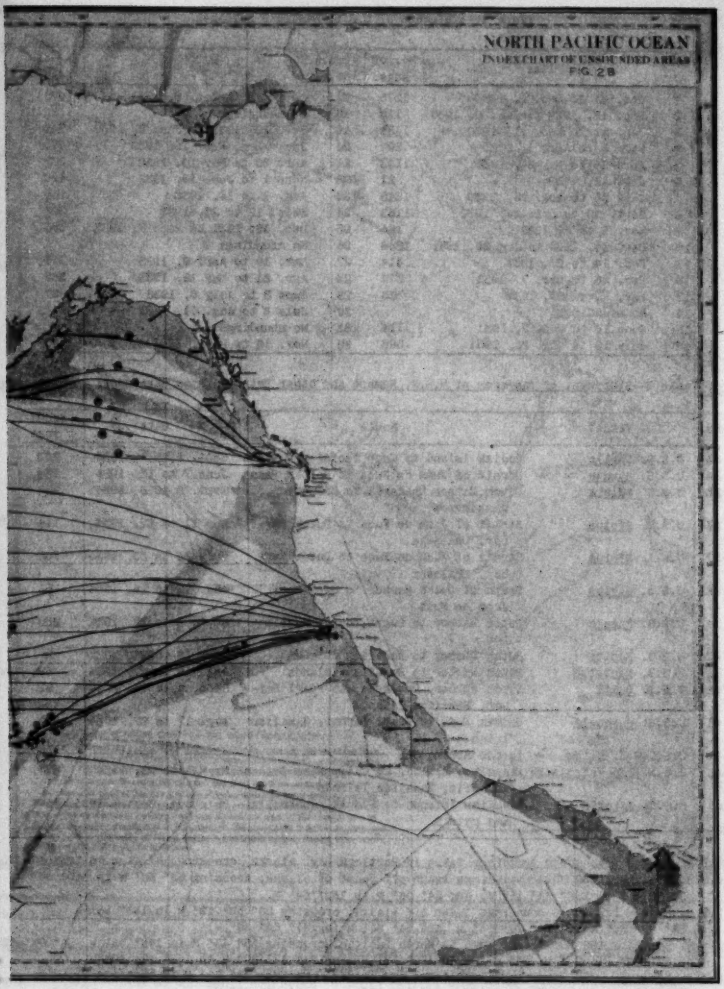
U.S.S. Bushnell - 188 sonic soundings taken en route Supan Deep to Pearl Harbor, Territory Hawaii, crossing 50° 38' N in 175° 30' W, 44° 29' 30" N in 168° 13' W, and 22° 12' N in 158° 33' W.

U.S.S. Bushnell - 22 sonic soundings taken in Supan Deep, crossing 50° 44' N in 147° W, and 50° 04' N in 175° 05' W.

U.S.S. Barracuda - 30 sonic soundings obtained off Seward, Alaska, crossing 59° 05' N in 149° 03' W.

Explanation--Portions of this chart colored gray are ocean-areas for which oceanic depths or deep-sea soundings have been observed and recorded on United States Hydrographic Office charts.

The U.S.S. Ramapo, between October 31, 1929, and December, 1933, crossed the North Pacific Ocean 32 times, taking sonic soundings on 28 passages mostly in unsounded areas, and using type S.E. 1987 (N. Electric Co.) machine, calibrated to a velocity of 1463 meters per second or 4800 feet per second. These passages with the exception of Nos. 6 (where only 21 soundings were taken), 14, 18, 26, and 31 are shown by heavy black lines with figures in circles showing the number of the passages (Table 1) in chronological order and arrows giving the direction of the passages.



Explanation (Continued)--Subsequent to 1933 the Ramapo operating with the Aleutian Islands Surveying Expedition, United States Navy, ran two lines of soundings as shown by lines of soundings Nos. 34 and 39 (Table 2).

The U.S.S. Bushnell was the only vessel equipped to make dynamic oceanographic soundings, and the data gathered at the 18 dynamic stations which she occupied taking serial observations from the surface to depths of 2000 fathoms, will form a valuable contribution in furnishing factors for correcting many of the Ramapo's sonic soundings. Her passage No. 43 from Unimak Pass to Pearl Harbor crossed 17 of the Ramapo's lines of echo soundings.

Table 1--Statement of U.S.S. Ramapo's passages

Pass. No.	Time	No. of sdgs.	Pass. No.	Time	No. of Sdgs.
1	Oct. 31 to Dec. 1, 1929	1275	17	Sept. 12 to Oct. 5, 1931	(972)
2	Dec. 13, 1929 to Jan. 6, 1930	110	18	No soundings	
3	Jan. 21 to Feb. 21, 1930	1438	19	Dec. 10, 1931 to Jan. 5, 1932	700
4	Mar. 5 to Apr. 1, 1930	592	20	Jan. 25 to Feb. 16, 1932	575
5	Apr. 28 to May 24, 1930	1143	21	Apr. 30 to May 10, 1932	207
6	June 11, 1930	21	22	June 1 to June 19, 1932	400
7	July 28 to Aug. 25, 1930	1315	23	Aug. 9 to 19, 1932	235
8	Sept. 20 to Oct. 14, 1930	1163	24	Sept. 12 to 27, 1932	324
9	Nov. 1 to 5, 1930	154	25	Dec. 16, 1932 to Jan. 5, 1933	353
10	Dec. 14, 1930 to Jan.20, 1931	1346	26	No soundings	
11	Feb. 14 to 23, 1931	414	27	Mar. 10 to Apr. 9, 1933	355
12	Feb. 26 to Mar. 7, 1931	374	28	Apr. 21 to May 19, 1933	365
13	Mar. 19 to 27, 1931	323	29	June 3 to July 8, 1933	94
14	No soundings		30	July 8 to Aug. 11, 1933	924
15	June 16 to July 7, 1931	1114	31	No soundings	
16	July 19 to Aug. 20, 1931	596	32	Nov. 10 to Dec., 1933	1340

Table 2--Statement of passages of U.S.S. Ramapo and other United States Government vessels

No.	Vessel	Route	Date	Soundings
33	U.S.S. Swallow	Kodiak Island to Cape Decision, Alaska	Sept. 7 to 9, 1934	103
34	U.S.S. Ramapo	Strait of Juan de Fuca to Unimak Pass	June 7 to 13, 1934	438
35	U.S.S. Oglala	Dutch Harbor, Unalaska, to Bremerton, Washington	Sept. 6 to 8, 1934	226
36	U.S.S. Sirius	Strait of Juan de Fuca to Dutch Harbor, Unalaska	May 11 to 27, 1934	174
37	U.S.S. Sirius	Strait of Juan de Fuca to Dutch Harbor, Unalaska	July 24 to 30, 1934	160
38	U.S.S. Sirius	South of Dutch Harbor to Strait of Juan de Fuca	Aug. 12 to 18, 1934	155
39	U.S.S. Ramapo	Dutch Harbor to Puget Sound, Washington	Sept. 5 to 12, 1934	358
40	U.S.S. Bonita	Dutch Harbor to Hawaiian Islands	Aug. 16 to 24, 1934	20
41	U.S.S. Nautilus	Dutch Harbor to Hawaiian Islands	Aug. 16 to 23, 1934	69
42	U.S.S. Quail	Dutch Harbor, Unalaska, to Pearl Harbor, Hawaiian Islands	Sept. 6 to 11, 1934	51
43	U.S.S. Bushnell	Unimak Pass to Pearl Harbor, Hawaiian Islands	Aug. 17 to 27, 1934	260
44	U.S.C.G.C. Haida	In the Bering Sea	Season of 1934	80
45	U.S.S. San Francisco	Acapulco, Mexico, to Clipperton Island and Hilo, Hawaiian Islands	May 11 to 23, 1934	(374)
46	U.S.S. Astoria	Hawaiian Islands to Sydney, Australia, and return	July, Aug., Sept., 1934	417

U.S.S. Bonita - 43 sonic soundings taken in Portlock Bay, Alaska, crossing 58° 41 N in 148° 49' W.

U.S.S. Holland - 280 sonic soundings taken off coast of Alaska, crossing 58° 58' N in 149° 00' W, 56° 01' N in 153° 41' 15" W, and 54° 06' N in 163° 54' W.

U.S.S. Bass - 179 sonic soundings taken off Alaska, crossing 58° 53' 12" N in 148° 56' W, 55° 57' 36" N in 153° 20' 15" W, and 54° 34' N in 157° 52' 30" W.

U.S.S. Bonita - 190 sonic soundings in North Pacific, crossing 58° 43' N in 148° 52' W, 54° 08' 45" N in 160° 37' 05" W, 33° 28' N in 159° 57' W, and 21° 17' 30" N in 158° 11' 30" W.

U.S.S. Norwhal - 355 sonic soundings taken off Alaska, crossing 56° 52' N in 151° 44' W, 55° 12' 30" N in 157° 00' W, and 58° 50' 15" N in 148° 56' 20" W.

U.S.S. Nautilus - 156 sonic soundings taken off Alaska, crossing 56° 38' 30" N in 151° 20' W, 53° 56' N in 159° 07' 30" W, and 54° 05' N in 160° 50' W.

U.S.S. Dolphin - 90 sonic soundings taken off Alaska, crossing 59° 10' N in 148° 57' W, 58° 37' 40" N in 151° 28' W, and 54° 07' N in 160° 56' W.

U.S.S. Nautilus - 69 soundings taken en route Dutch Harbor to Hawaiian Islands, crossing 53° 22' N in 165° 35' W, and 21° 44' N in 158° 21' 30" W.

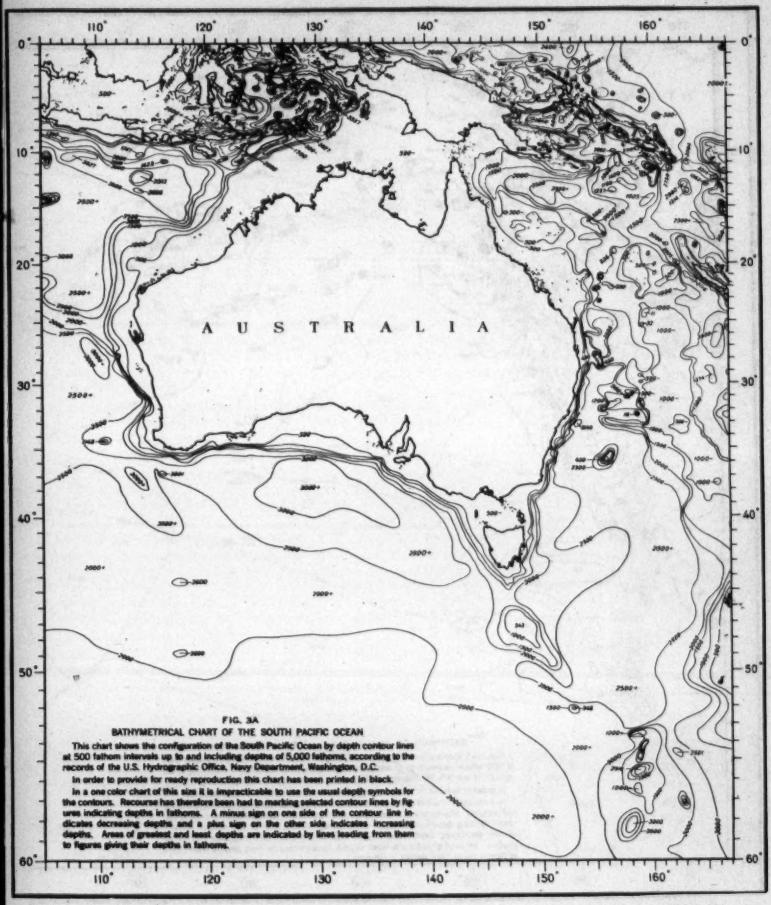


FIG. 3A

BATHYMETRICAL CHART OF THE SOUTH PACIFIC OCEAN

This chart shows the configuration of the South Pacific Ocean by depth contour lines at 500 fathom intervals up to and including depths of 5,000 fathoms, according to the records of the U.S. Hydrographic Office, Navy Department, Washington, D.C.

In order to provide for ready reproduction this chart has been printed in black. In a one color chart of this size it is impracticable to use the usual depth symbols for the contours. Recourse has therefore been had to marking selected contour lines by figures indicating depths in fathoms. A minus sign on one side of the contour line indicates decreasing depths and a plus sign on the other side indicates increasing depths. Areas of greatest and least depths are indicated by lines leading from them to figures giving their depths in fathoms.

U.S.S. Hannibal - 100 sonic soundings in the Caribbean Sea, crossing 9° 53' N in 79° 41' 10" W 12° 26' 15" N in 78° 25' 30" W, and 19° 01' N in 74° 38' 15" W.

U.S.S. Nokomis - 352 sonic soundings in North Atlantic, crossing 9° 48' 45" N in 79° 39' W, 20° 10' N in 74° 07' W, and 36° 32' N in 75° 36' W.

U.S.S. Ramapo - Line of 430 sonic soundings in North Pacific from Dutch Harbor to Puget Sound, crossing 52° 16' 30" N in 169° 33' 30" W, 50° 18' N in 152° 56' W, and 48° 39' 30" N in 125° 32' 18" W.

U.S.S. West Virginia - 47 sonic soundings obtained in the Straits of Florida and Santaren Channel, crossing 25° N in 80° W and 23° N in 79° W.

U.S.S. Oglala - 226 sonic soundings taken from Dutch Harbor, Unalaska, to Bremerton, Washington, crossing 53° 59' N in 165° 22' 30" W, 54° 32' 00" N in 143° 26' 15" W, and 48° 59' 30" N in 127° 08' W.

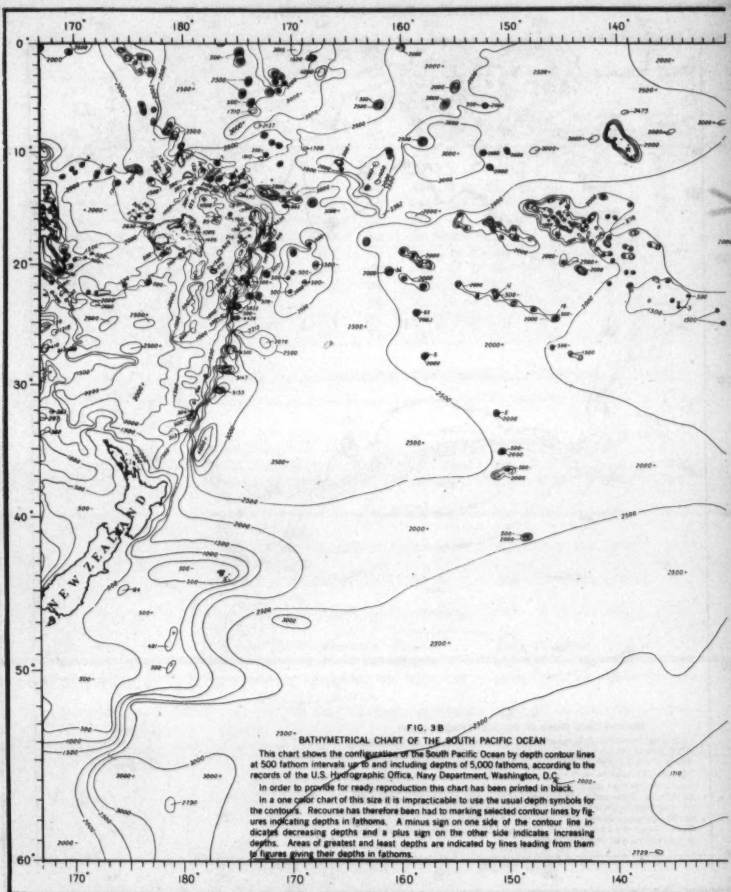


FIG. 3B

BATHYMETRICAL CHART OF THE SOUTH PACIFIC OCEAN

This chart shows the configuration of the South Pacific Ocean by depth contour lines at 500 fathom intervals up to and including depths of 5,000 fathoms, according to the records of the U.S. Hydrographic Office, Navy Department, Washington, D.C.

In order to provide for ready reproduction this chart has been printed in black. In a one color chart of this size it is impracticable to use the usual depth symbols for the contours. Recourse has therefore been had to marking selected contour lines by figures indicating depths in fathoms. A minus sign on one side of the contour line indicates decreasing depths and a plus sign on the other side indicates increasing depths. Areas of greatest and least depths are indicated by lines leading from them to figures giving their depths in fathoms.

U.S.S. Swallow - 103 fathometer-soundings in Gulf of Alaska, crossing 57° 59' 50" N in 152° 25' 50" W, and 56° 02' 20" N in 134° 31' 30" W.

U.S.S. Oklahoma - Line of 23 fathometer-soundings in Santaren Channel, crossing 23° 00' N in 79° W.

U.S.S. Ranger - 38 sonic soundings in South Atlantic, crossing 34° 23' 30" S in 52° 46' 30" W, and 5° 05' S in 34° 58' W.

U.S.S. Oglala - Line of 183 sonic soundings obtained en route San Diego, California, to Honolulu, Territory Hawaii, crossing 32° 33' N in 117° 24' 55" W, 26° 16' 20" N in 145° 16' 30" W, and 21° 14' 04" N in 157° 40' 15" W.

U.S.S. Augusta - Line of 22 fathometer-soundings taken during passage from Tsingtao to Chinwangtao, China, crossing 38° 39' 10" N in 121° 00' 25" E.

U.S.S. Bushnell - Line of 156 sonic soundings taken en route Honolulu, Territory Hawaii, to San Diego, California, crossing 23° 01' N in 154° 06' W, 27° 02' N in 141° 16' 30" W, and 32° 34' N in 117° 23' W.

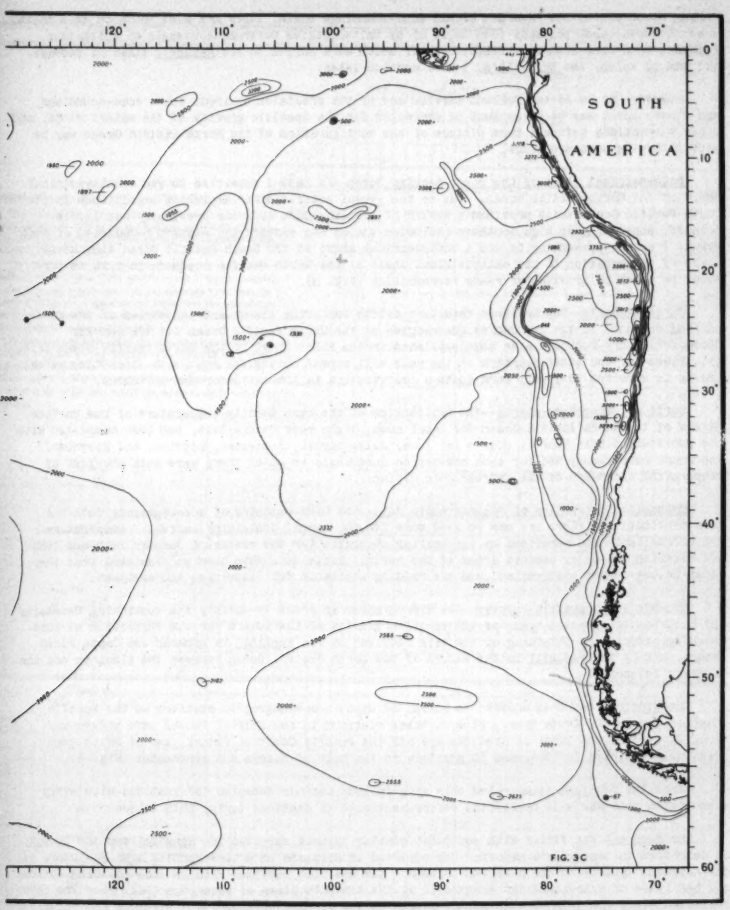


FIG. 3C

Oceanic depths--The fifth of a series of annual publications presenting lists of oceanic depths in several oceans has been recently published by the Hydrographic Office as Hydrographic Office Publication No. 201D, "List of oceanic depths, 1934, North Atlantic Ocean and Caribbean Sea." While annuals Nos. 210A and 210C contain 18,222 soundings recorded by the U.S.S. Ramapo in 32 trans-Pacific crossings, she has made two other crossings during the past year.

Previous lists published are: Nos. 210, 210A, 210B, and 210C, containing, respectively, lists of soundings for the North Atlantic, North Pacific, Pacific, and North Pacific oceans.

Unsounded areas of the North Pacific Ocean--Again I present to you a chart showing the unsounded areas of the North Pacific Ocean and on which the portions colored grey are for oceanic areas for which soundings have been observed or recorded on Hydrographic Office charts (Fig. 2) In addition to the Ramapo's 32 passages (see Table 1) across the North Pacific Ocean since 1929,

during which period she recorded 18,222 echo-soundings taken, there are also shown on this chart some thirteen other passages (see Table 2) by United States Government vessels on which they recorded 2885 echo-soundings taken, four of which were normal to the Ramapo's lines of passage, and one of which, the Bushnell's, I will mention later.

However, to be of the fullest service and of the precision desired, these echo-soundings and others which may be taken must be corrected for the specific gravity of the water, slope, and other corrections before a true picture of the configuration of the North Pacific Ocean may be made utilizing echo-soundings.

Bathymetrical chart of the South Pacific Ocean--In 1933 I submitted to you a bathymetrical chart of the North Pacific Ocean. Due to the recent activities of exploring expeditions in the South Pacific Ocean which provided a wealth of sounding data in areas previously but little sounded, especially in high southern latitudes and on the eastern and western boundaries of that Ocean, I am now presenting to you a bathymetrical chart of the South Pacific Ocean similar in style of presentation to the bathymetrical chart of the North Pacific Ocean in that it is produced in black to provide for ready reproduction (Fig. 3).

Current-charts--The traverse resultant drifts including trends and tendencies of the resulting currents in the one-degree quadrangles of the North Pacific Ocean for the quarter December-January-February have been published on the Pilot Chart of the North Pacific Ocean (Fig. 4). Those for the other quarters of the year will appear during the months to which they refer, and it is expected they will form quite a contribution to the navigator and scientist.

Surface-temperature charts--The publication of the mean monthly temperature of the surface-waters of the North Pacific Ocean for local noon, begun year before last, has been completed with the publication this year of charts for June, July, August, September, October, and November. The means were summarized for each one-degree quadrangle in which there were data provided by cooperating observers of the Hydrographic Office.

Mechanical extraction of oceanographic data--The card-punching of oceanographic data has been continued and there are now on hand some 240,000 cards, containing current, temperature, and concomitant data submitted by cooperating observers for the months of January 1932 and 1933 and covering the major oceanic areas of the world. These data have been so tabulated that they refer to one-degree quadrangles, and are readily available for inspection and analyses.

Dynamic oceanographic surveys--The Hydrographer, in order to satisfy the continuing necessity for securing the precise value of the specific gravity of the waters for the correction of echo-sounding, ordered the obtaining of the data required by the Hannibal in Panaman and Costa Rican waters, and by the Bushnell in the waters of the North Pacific Ocean between the Aleutian and the Hawaiian Islands.

The Hannibal has been ordered to occupy 36 dynamic oceanographic stations on the Pacific Coast of Panama and Costa Rica. Five of these stations in the Gulf of Panama were previously occupied in 1933 and 1934; 11 stations are off the Pacific Coast of Panama, two of which were previously occupied in 1933; and 20 stations in the Gulf of Nicoya and approaches (Fig. 5).

Since the Hannibal inaugurated this work in 1933 she has occupied 187 stations with every expectation that she will occupy the before-mentioned 36 stations during this season.

The Bushnell was fitted with equipment similar to that supplied the Hannibal and the Gannet, as described in last year's report. She occupied 18 stations on a line running from southward of the Aleutian Islands to the Hawaiian Islands. She was also equipped with an echo-sounding device and her lines of echo-soundings crossed 17 of the Ramapo's lines of soundings (Fig. 2). The data collected along the line of echo-soundings and at the dynamic oceanographic stations she occupied will constitute a valuable contribution as they were obtained in localities where they were needed for urgent economic and scientific purposes. Roger Revelle of the Scripps Institution of Oceanography, La Jolla, California, accompanied the Bushnell by permission of the Navy Department, and assisted greatly in the operations.

One of the United States Naval vessels conducting surveys among the Aleutian Islands this season is being fitted to obtain dynamic oceanographic data. Her program is to occupy stations shown on Figure 6, reoccupying some of the stations previously occupied by the U.S.S. Gannet in 1933.

Both the Scripps Institution of Oceanography at La Jolla, California, and the Oceanographic

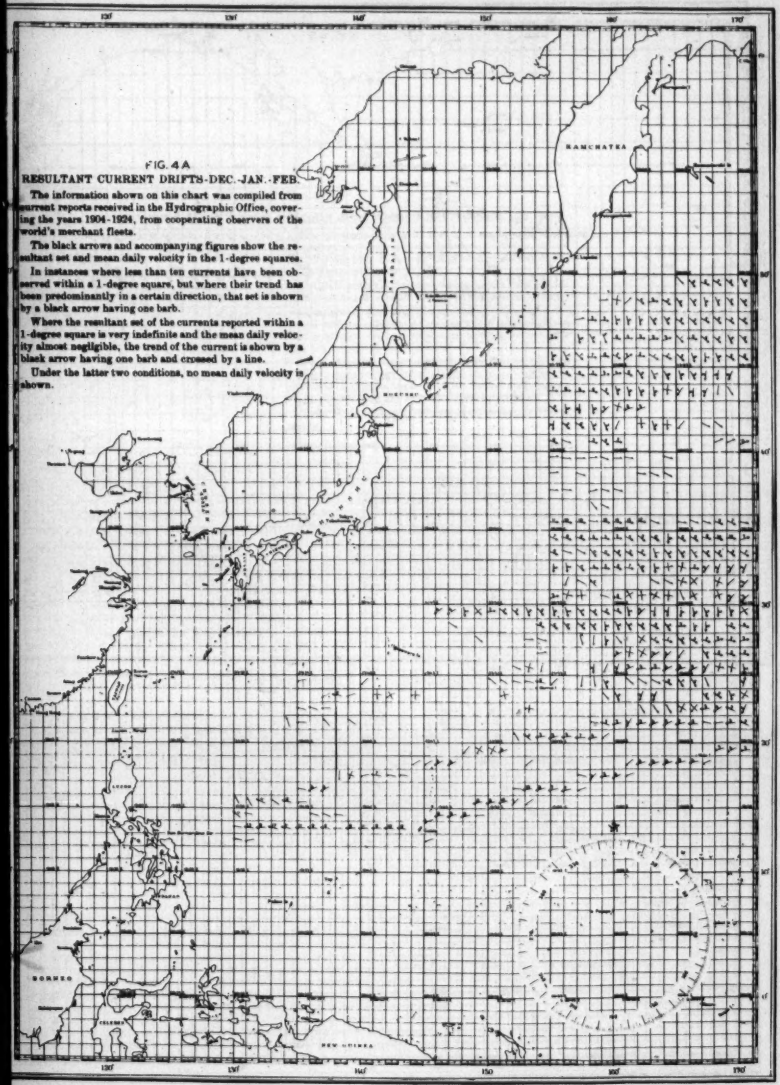


FIG. 4A

RESULTANT CURRENT DRIFTS-DEC.-JAN.-FEB.

The information shown on this chart was compiled from current reports received in the Hydrographic Office, covering the years 1904-1924, from cooperating observers of the world's merchant fleets.

The black arrows and accompanying figures show the resultant set and mean daily velocity in the 1-degree squares.

In instances where less than ten currents have been observed within a 1-degree square, but where their trend has been predominantly in a certain direction, that set is shown by a black arrow having one barb.

Where the resultant set of the currents reported within a 1-degree square is very indefinite and the mean daily velocity almost negligible, the trend of the current is shown by a black arrow having one barb and crossed by a line.

Under the latter two conditions, no mean daily velocity is shown.

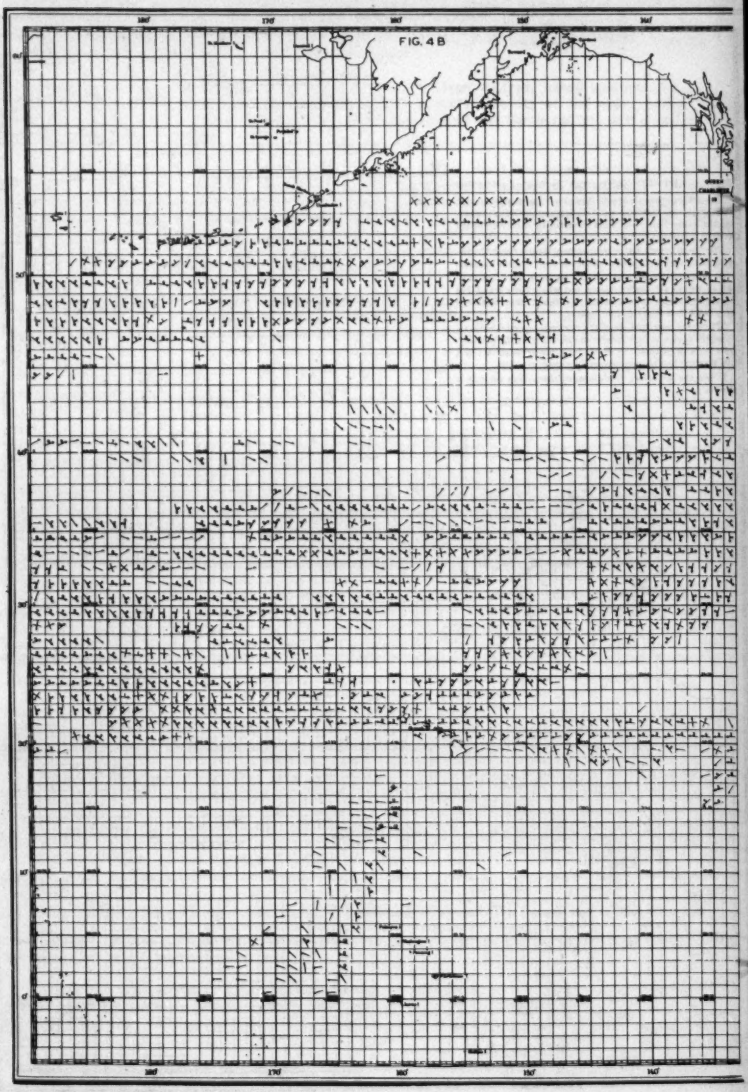


FIG. 4B

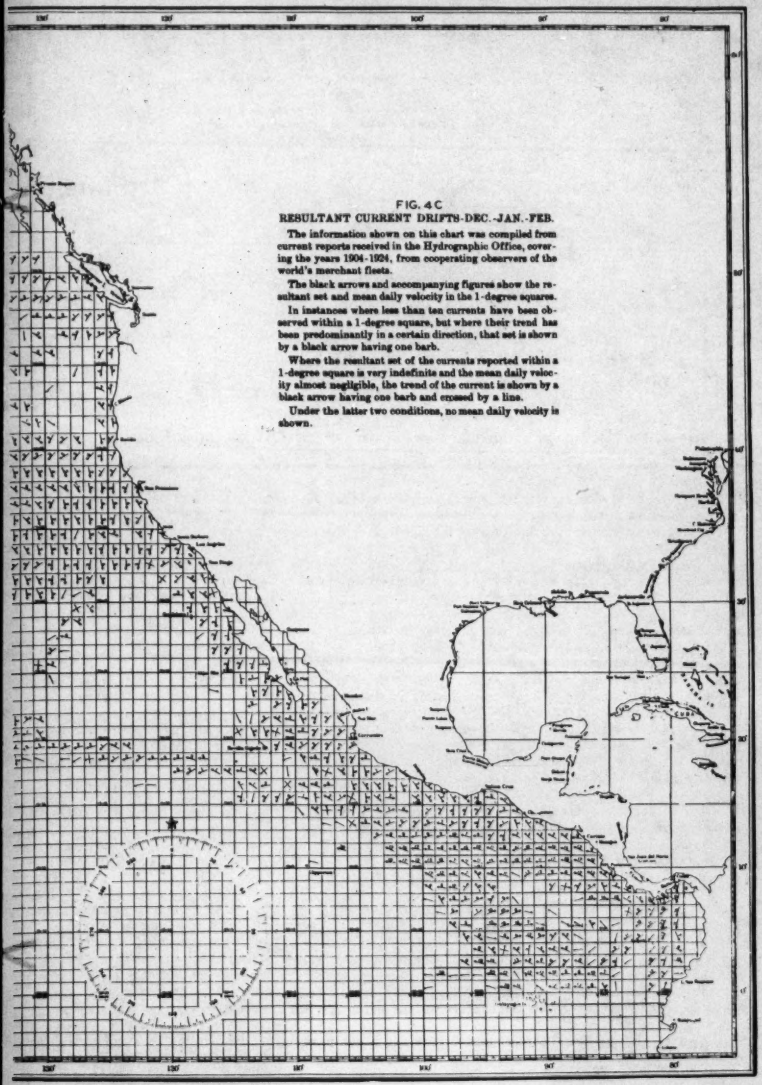


FIG. 4 C

RESULTANT CURRENT DRIFTS-DEC.-JAN.-FEB.

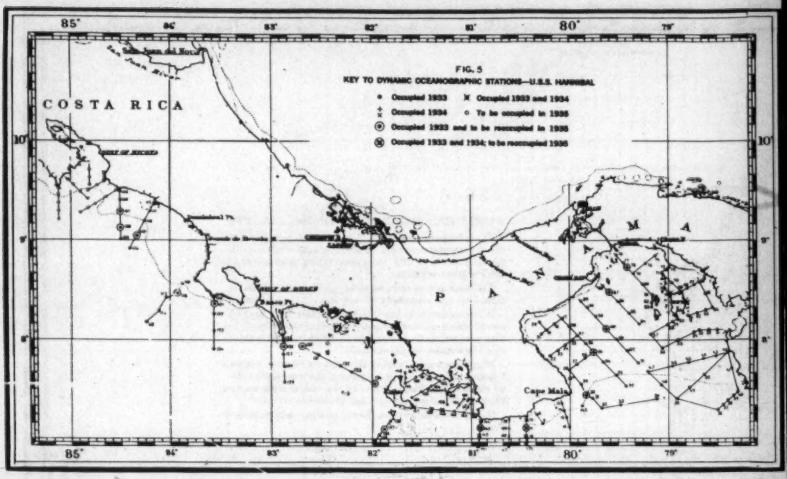
The information shown on this chart was compiled from current reports received in the Hydrographic Office, covering the years 1904-1924, from cooperating observers of the world's merchant fleets.

The black arrows and accompanying figures show the resultant set and mean daily velocity in the 1-degree squares.

In instances where less than ten currents have been observed within a 1-degree square, but where their trend has been predominantly in a certain direction, that set is shown by a black arrow having one barb.

Where the resultant set of the currents reported within a 1-degree square is very indefinite and the mean daily velocity almost negligible, the trend of the current is shown by a black arrow having one barb and crossed by a line.

Under the latter two conditions, no mean daily velocity is shown.



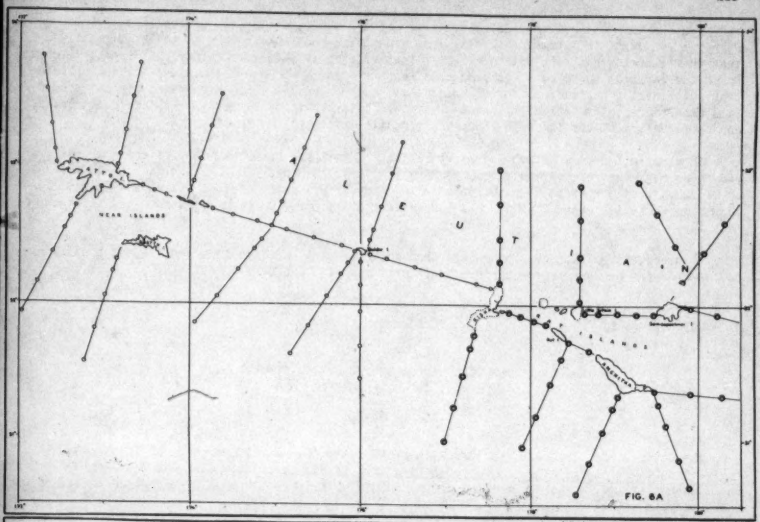
Laboratories of the University of Washington at Seattle, Washington, aided the Hydrographic Office whenever possible with the dynamic oceanographic work in hand and the Hydrographer desires to express his appreciation and thanks for their continued cooperation.

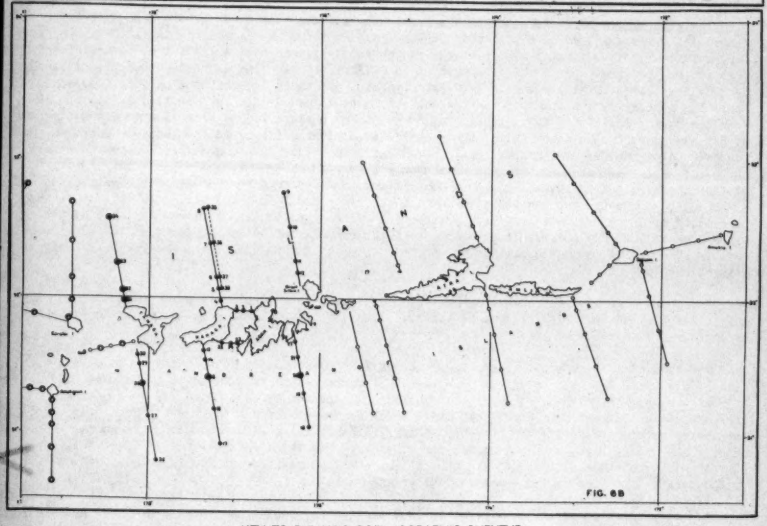
Special utilization of echo-sounding data--While the Hydrographer has recognized and still recognizes the necessity of securing quantitative hydrodynamic data for reducing echo-soundings to precise measurements, to delineate the configuration of oceans with certainty, the Hydrographic Office contemplates the placing on its general charts of the oceans, and in depths recognized as extending below 100 fathoms, the uncorrected values obtained by echo where no correction-data are available. The uncorrected echo-soundings are to be of figures differing in color or form from the corrected echo- or wire-soundings. In fact, from the standpoint of the navigator using echo-sounding devices, a chart presenting uncorrected echo-sounding values will be of a readier and more expeditious use than a chart presenting corrected or precise values. The navigator, using a chart with corrected values, must have on hand tabulated data--at present not comprehensive considering oceanic areas covered or facts contained--which he must use to correct or translate his echo-soundings in order to obtain suitable measurement for comparison with the charted values in order to orient or check his position. The process of interpolation is lengthy and requires great care and experience.

The charts, as contemplated, are to carry, in addition to corrected soundings (wire and echo) and uncorrected echo-soundings, notes informative of the sounding velocity upon which the uncorrected echo-soundings were based, and the mean monthly, seasonal, or annual corrections to be applied to echo-soundings based upon available data relating to changes in the specific gravity of the water from the surface to the thermocline.

It is believed that the average seasonal correction to be considered will be approximately one half of one per cent. Therefore, the navigator may, if given a chart showing uncorrected echo-soundings, be enabled to determine with facility and practical accuracy relative depths providing him with the navigational data he requires to get a measurement of depth for a check against charted corrected soundings, instead of using what might be termed a lengthy back-handed procedure of taking echo-soundings and reducing them by tables which are at present inadequate and where, in many cases, the temperature of the water and salinity may not be known.

Magnetic charts--The Hydrographic Office has about ready for issue world charts showing the values of the magnetic elements, declination, dip, and horizontal intensity, laid down as lines of equal value for the epoch 1935. These charts cover all land and sea areas and were constructed from data largely supplied by the Carnegie Institution of Washington.





KEY TO DYNAMIC OCEANOGRAPHIC SURVEYS

Stations occupied by the U. S. S. Gannet in 1933.
Stations to be occupied in the future.
Stations to be occupied during 1935.

You may know the British Admiralty is to build a non-magnetic ship of the type of the Carnegie for magnetic, atmospheric-electric, and oceanographic work at sea, and I am gratified that the Admiralty has seen fit to enter in these fields of endeavor, gathering information upon which the maritime world so largely depends for its safety. However, I believe with Dr. Fleming that, considering the vast extent of the oceans, another vessel could advantageously be used in this important geophysical work, and I trust that this country will have such a one constructed, and operated especially in areas where its economic interests mainly lie.

In closing I desire to express my regret that I will not have the honor of again addressing you as Hydrographer of the United States Navy as I have been ordered to leave Washington for duty as Commandant of the First Naval District with headquarters at the United States Navy Yard, Boston, Massachusetts, where it will be a source of gratification to have you communicate with me or make me a personal visit.

My associations with this body have been most pleasant and fruitful, and I trust that it may be possible for me as a member to meet again with you at these annual meetings.

U. S. Hydrographic Office,
Washington, D. C.

OCEANOGRAPHIC WORK CARRIED ON BY THE UNITED STATES COAST GUARD DURING 1934 AND PLANS FOR 1935

H. G. Hamlet

The Coast Guard, following the practice of the past few years, assigned two first-class cruising cutters, the Mendota and Pontchartrain, to the duties of International Ice Patrol for the season of 1934. Also, in addition, the 125-foot patrol boat General Greene was detailed as oceanographic vessel.

The General Greene, with which we are particularly interested, took oceanographic observations of the temperature and salinity in the area around the Grand Banks from April 17 to June 29. A series of four current-maps was constructed and delivered to the Ice Patrol cutter on duty. This information was used by the Ice Observation Officer to guide and warn the steamships throughout the ice season. The first current- (hydrodynamic) map indicated that the Labrador Current in April was setting farther inshore than normal. As a consequence of this, practically all of the icebergs during April were swept inshore onto the northern slope of the Grand Banks. The month of May saw current-conditions returning to normal with bergs drifting in the Labrador Current southward along the eastern side of the Grand Banks. The cold current, however, did not penetrate southward as far as normal. For that reason only a very few bergs succeeded in drifting south of the 43rd parallel latitude. Early in June it was observed from the current map constructed by the General Greene that the Labrador Current was pinched off by a wedge of warm Atlantic water associated with the Gulf Stream, which pressed inshore to the westward against the slope of the Grand Bank in latitude 44°. This development in the currents effectually blockaded icebergs from further threatening the steamships on the United States to Europe tracks and the Ice Patrol was discontinued on June 29.

It can be seen from the foregoing how the Coast Guard is employing in particular the so-called Bjerknes methods of hydrodynamic surveys to assist in providing greater safety to trans-Atlantic navigation.

The fact that in 1934 there were fewer icebergs which succeeded in drifting south of the Tail of the Grand Bank had no effect upon the total number which drifted south of the latitude of Newfoundland. It will be recalled that for several years the Coast Guard has been making a forecast of the number of icebergs that drift south of Newfoundland. In 1934 the prediction was for approximately 650 bergs, or an iceberg season somewhat heavier than normal. The normal number is 420 bergs. It will be interesting, therefore, to learn that the actual count tallied closely with that forecasted. In this connection, the iceberg-forecast for 1935 is approximately 350 bergs, or an ice season somewhat lighter than normal.

At the expiration of the Ice Patrol in 1934 the General Greene ran two lines of oceanographic stations across the continental shelf northeast of Newfoundland and also a complete traverse of the Labrador Sea from southern Labrador to Cape Farewell, Greenland. The object of this survey was to reoccupy the key-stations previously taken in approximately the same positions as during previous summers, in order to detect what variations, if any, had occurred, in the temperature

and volume of the current. Floyd M. Soule, Senior Physical Oceanographer, United States Coast Guard, was in charge of the oceanographic observations during the Ice Patrol season, as well as the oceanographic work during the post-season cruise. A brief report of the oceanography for 1934 is contained in Coast Guard Bulletin No. 24.

In addition to the hydrodynamic surveys, the General Greene took approximately 500 soundings with the fathometer, for which accurate positions and correction-data are available. The usual fortnightly maps of surface-temperatures in the Grand Banks area were constructed throughout the ice season, based upon thousands of the temperature-reports radioed the Ice Patrol cutter by passing steamships. These maps are published in the annual Ice Patrol Bulletin.

It will be recalled that the oceanographic material collected by the United States Coast Guard in the northwestern North Atlantic for the summers of 1928, 1931, and 1933 are being examined and prepared for publication at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, by the three oceanographers who participated in the oceanographic work of the Coast Guard during those years. It is intended to publish the scientific results as Part II of Coast Guard Bulletin No. 19 (Parts I and III have already been published).

In connection with the final report there have been some interesting findings, some of the features of which may be briefly mentioned here. For example, it has been found that the west Greenland Current, which flows northward along the west coast of Greenland, is subject to important variations. The best means of detecting such variations have resulted from the construction of velocity-profiles and then from these to compute the volume of flow expressed in millions of cubic meters per second. In this manner, the west Greenland Current was found to vary during the years of observation from a maximum of six million cubic meters per second to a minimum of one million cubic meters per second. The average temperature of the west Greenland Current has next been computed and from this the rate of heat-supply expressed in degrees-Centigrade-millions-cubic-meters-seconds. The rate of heat-supply appears to be the most accurate method known to compare currents and determine quantitatively the extent of their variations. In the summer of 1928, for example, the Coast Guard found that a relatively large increase in the rate of heat-supply of the west Greenland Current existed over any other years for which we have records. This surplus supply of heat transported northward toward frozen iceberg-producing glaciers along the west coast of Greenland may have been the direct cause for the unusual amount of floating ice when more than 1300 icebergs drifted south of Newfoundland in the spring and summer of 1929.

At the present time the Ice Patrol for the season of 1935 has been inaugurated. The General Greene is carrying out the oceanographic work of supplying the current-maps for the Coast Guard cutter on Ice Patrol duty. It is intended that at the termination of the ice season this year (1935) to have the General Greene conduct an oceanographic survey of an extensive and little known sea-area lying several hundred miles east of Newfoundland and south of Greenland. It is expected that this region, bordering as it does on the eastern side of the already-surveyed areas by the Coast Guard, may play an important role in the drift of Arctic ice. The system of circulation in this area has indicated from the Coast Guard's observations around the western margin that it is subject to two general types, one in which the northerly moving masses of Atlantic water outside the Newfoundland and Labrador slopes are discharged directly northward along the west coast of Greenland and augment the west Greenland Current; the other in which this inner margin of the Atlantic Drift is turned eastward in the vicinity of the 50th parallel of latitude. Both these types of circulation may have directly or indirectly an important influence upon the iceberg problem.

The General Greene, on its post-season cruise of 1935, will be equipped with extra sonic oscillators capable of obtaining accurate soundings to depths of 4000 meters and greater. The bottom topography of the North Atlantic Basin in the region planned for the General Greene's survey is believed to exert an important effect on the circulation of the bottom-water of the North Atlantic. Whether or not, as some oceanographers believe, the Reykjanes Ridge, which in its 4000-meter isobath southwest of Iceland, connects with an extension of the Grand Banks to form the so-called Newfoundland Ridge, will in all probability be definitely ascertained by the General Greene this summer.

U. S. Coast Guard,
Washington, D. C.

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

Paul A. Smith

The United States Coast and Geodetic Survey, in connection with its offshore surveys, has in recent years obtained much information of interest to oceanographers. The greater part of such data is incident to regular charting activities, such as the temperatures and salinities that are taken for obtaining fathometer corrections, and the velocity of sound for use in radio-acoustic ranging. The demands by modern shipping for more detailed development of characteristic topography of the ocean-bottom are due mainly to the increasing use of echo-sounding equipment by merchant vessels. This, in turn, requires more accurate control than has been used in the past for offshore surveys, and radio-acoustic ranging has been found to be satisfactory. The application of these acoustic methods requires complete and comprehensive temperature- and salinity-observations, and such observations are taken by all the ships engaged in this work. The results of these offshore surveys, in addition to their importance to shipping, have disclosed some remarkable features of submarine topography which may have an influence on important geological problems.

A number of deep submarine valleys have been found on the edge of the Atlantic Continental Shelf, and a sketch of one is shown on Figure 1. The Master of the steamer City of Norfolk reported this valley on his course while approaching Chesapeake Bay before surveys had been extended southward to include it. The ships Oceanographer, Lydonia, and Gilbert at present are working in this area, and this summer will complete the work further to the southward. Outline maps of the United States and possessions are shown here to indicate the offshore areas which have been surveyed by acceptable methods up to this time (Figs. 2, 3, 4, and 5). During the past year over 14,000 square miles of offshore areas were surveyed by radio-acoustic methods.

In addition to the offshore work, which is of primary interest to oceanographers, 15 additional parties are conducting hydrographic surveys along the coasts. During the past year all parties (including the offshore parties) ran over 110,000 miles of sounding lines, embracing an area of approximately 50,000 miles and recorded over 2,500,000 soundings.

The accuracy of the data obtained by the various acoustic methods now used by the Coast and Geodetic Survey is described in these Transactions in Appendix A of the report of the Union's Special Committee on Geophysical and Geological Study of Oceanic Basins. In that appendix, which describes in brief the various methods, it is stated that the accuracy of position obtained by visual fix from shore-control, as of a given survey, is approximately 1 part in 500 to 1000, depending on the relative positions of the control-stations and the distances offshore. For radio-acoustic ranging positions, the accuracy is about 1 part in 200 to 500, again depending on the locality surveyed and the positions of the shore-stations. From experience with comparisons over several years, and a consideration of the various instrumental difficulties, it is believed that the soundings are accurate to within one-half of one per cent in depths up to 10 fathoms, to within about one per cent for depths between 10 and 200 fathoms, and to within about 3 per cent in depths over 200 fathoms, depending upon the character of the bottom and the type of instrument used. A recent development, the Dorsey fathometer, has increased the accuracy of soundings in depths less than 10 fathoms, and has made possible the more detailed sounding of these shoaler areas. This instrument, which has been installed on two ships, gives 20 flashes per second on the dial, and the depth appears as an almost continuous line of light.

Studies of the experiments made by the ships Pioneer and Guide, in 1933, show that the apparent horizontal velocity of sound as used in radio-acoustic ranging in deep water depends to a certain extent upon the depth, and upon the distance of the surveying ship from the hydrophone. Oscillograph records of a number of bombs fired by these vessels in 1933 indicate that the rays of the sound wave follow a path similar to that shown in Figure 6. Additional tests were made by these vessels in December 1934; and, although the results of the latter are not available, considerable information has been obtained which will make possible greater accuracy in radio-acoustic ranging. The instrumental equipment and the procedure for this work have been improved and simplified. A report on the experiments by the Commanding Officer of the ship Pioneer has been published in preliminary form and gives complete data and results of the 1933 experiments in the Santa Barbara Islands, California Coast.

The ships Oceanographer and Lydonia confirmed the results of the Pioneer and Guide by simple tests made off the edge of the Continental Shelf, Virginia Coast. These vessels have used a combination of taut wire and Sun azimuth traverse for controlling the surveys on the Continental Shelf, and the method has improved both the accuracy and the economy of this type of work. Figure 7 shows the system of traverse used, and the closing error of the large loop, which was 464

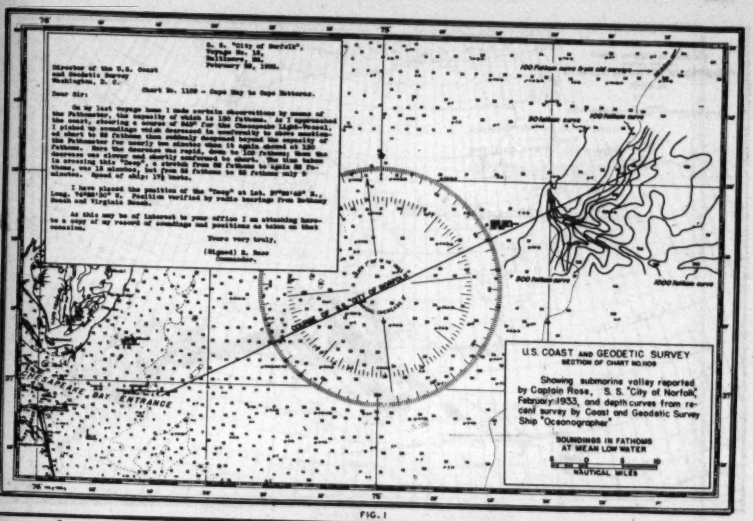

U.S. COAST AND GEODETIC SURVEY
SECTION OF CHART NO.1108
Showing submarine valley reported by Captain Rose, S.S. "City of Norfolk", February 1933, and depth curves from recent survey by Coast and Geodetic Survey Ship "Oceanographer"
SOUNDINGS IN FATHOMS AT MEAN LOW WATER
NAUTICAL MILES
100 Fathom curve from old surveys
100 fathom curve
200 fathom curve
500 fathom curve
1000 fathom curve
CHANNEL
ENTRANCE

FIG. 1

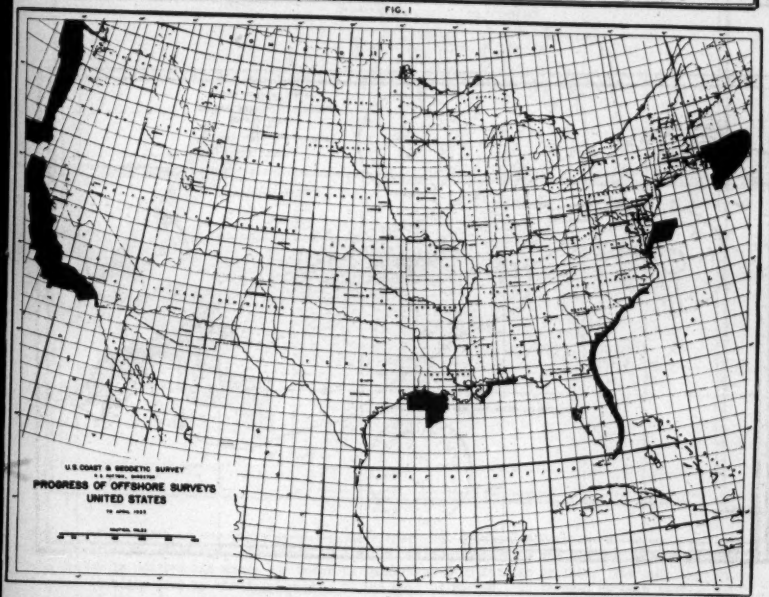

U.S. COAST & GEODETIC SURVEY
PROGRESS OF OFFSHORE SURVEYS
UNITED STATES

FIG. 2

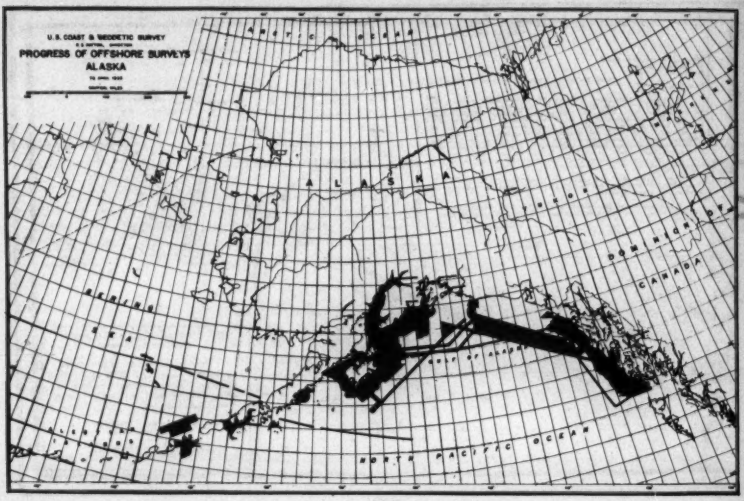

U.S. COAST & GEODETIC SURVEY
PROGRESS OF OFFSHORE SURVEYS
ALASKA
ARCTIC OCEAN
ALASKA
GULF OF ALASKA
NORTH PACIFIC OCEAN
CANADA

FIG. 3

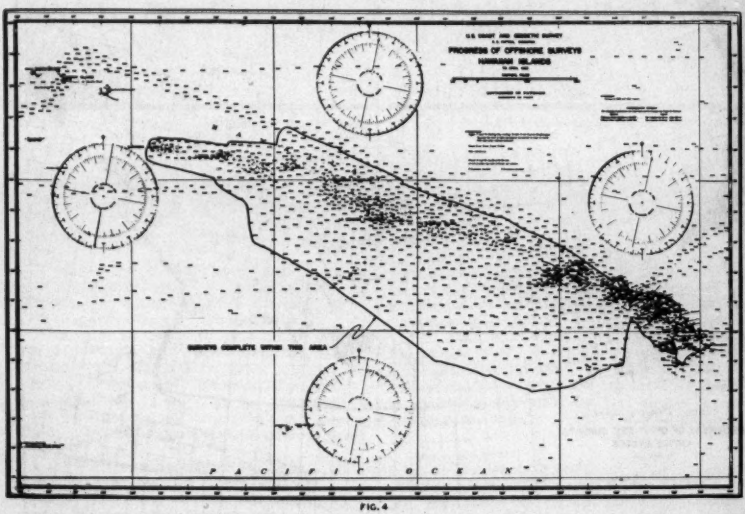

PROGRESS OF OFFSHORE SURVEYS
HAWAIIAN ISLANDS
SURVEYS COMPLETE WITHIN THIS AREA
PACIFIC OCEAN

FIG. 4

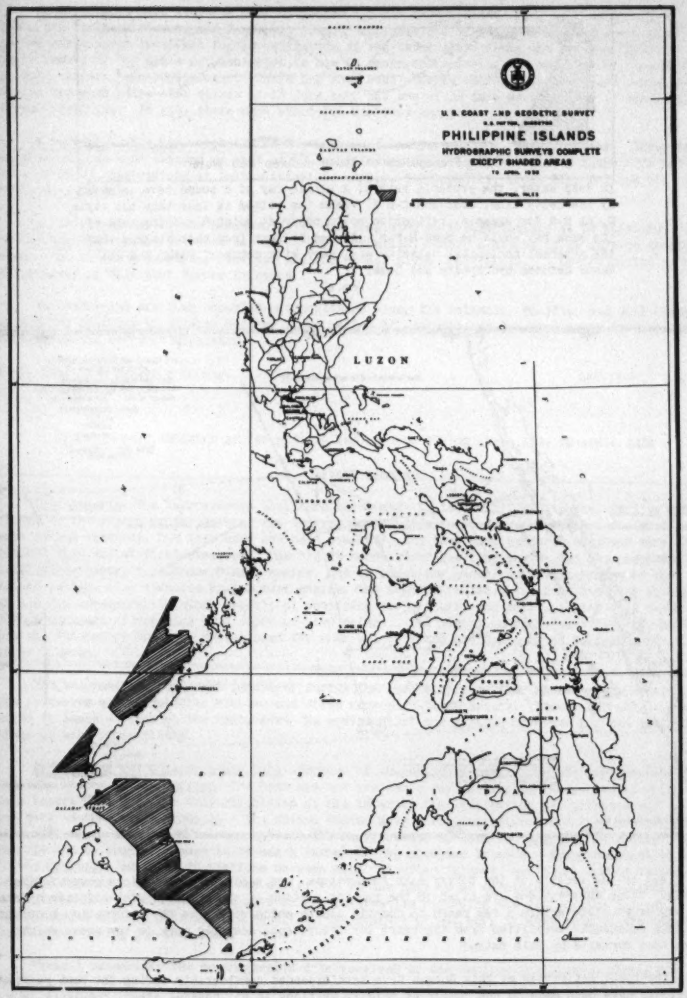
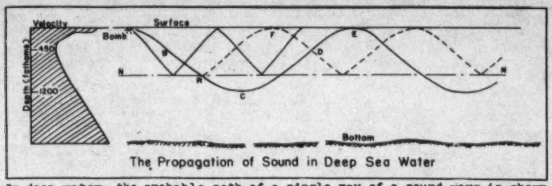


FIG. 5

meters. The length of the traverse was about 115 statute miles, which makes the error about 4.0 meters per mile. This type of control is limited to the Continental shelves of the coasts where the bottom is uniform and where the water is shoal--about 50 fathoms or less. The same type of control is being used by the Hydrographer in the Gulf of Mexico. It is used by both parties to supplement the radio-acoustic ranging.



The Propagation of Sound in Deep Sea Water

In deep water, the probable path of a single ray of a sound-wave is shown by the heavy line, bomb-B-R-C-D-E. When the bottom is less than the depth C, at N-N for example, reflection would occur at point R and the path of the same ray would be bomb-R-F-D. It can be seen from this diagram that the apparent horizontal velocity will vary with depth of ocean and distance between hydrophone and bomb.

FIG. 6

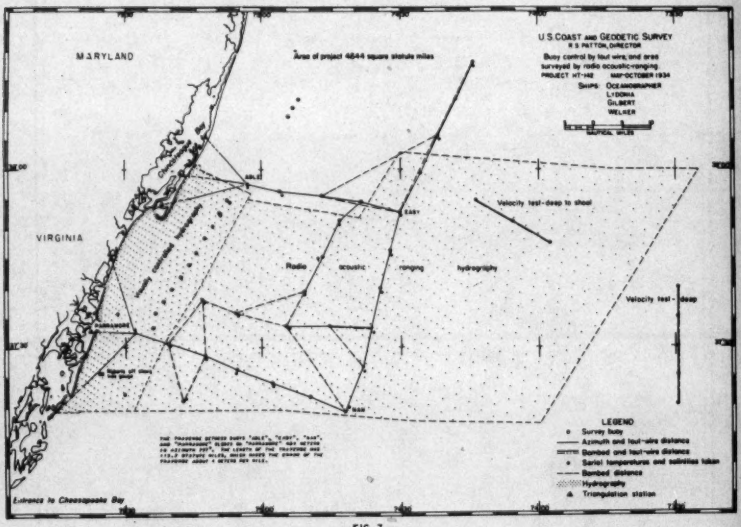


FIG. 7

All of the vessels of the survey make temperature- and salinity-observations several times daily. These observations are filed in the records section of the Bureau. With sufficient data, it may be possible within a few years to compile charts which will give the information necessary to take dependable velocities from the chart for future aqua-acoustic work in the areas which have been surveyed by this method.

The tidal activities of this Bureau have been expanded considerably during the past year. Additions have been made to the number of primary stations in all coastal areas, resulting in a closer spacing of tie-in points for the first-order level-net. A large increase in the number of secondary stations along the intracoastal waterways has resulted from accelerated activity in hydrographic surveys. Tidal bench-marks are established at all stations so that datum-planes of tidal definition are now available for these coastal points.

Tidal surveys have recently been completed for the Oregon coast, Florida west coast, St. Johns and Savannah rivers, and Nantucket Sound. All stations of the Oregon survey were connected to the first-order level-net for investigation of sea-level slope along the Pacific Coast. A tidal survey of the State of Washington is now in progress, covering the outer coast, the Strait of Juan de Fuca, and Puget Sound. There has also been a large increase in the tidal current-work during the past year. Two series of 15 days each and one of 29 days were secured in important harbor entrances. In all, there were about 225 stations occupied.

A current-survey was completed in Nantucket and Vineyard sounds, Massachusetts. Three days of observations were secured at each of 47 current-stations. In this vicinity there also have been obtained observations at four lightships, namely, Handkerchief, Cross Rip, Pollock Rip, and Stone Horse Shoal.

A current-survey of the Savannah River was completed with observations at 38 stations. One of the stations in the entrance was of 15 days' duration. Other stations of 15 days or longer were: One at Miami Entrance, Florida, and one at San Diego, California. A 29-day series is now in progress at Galveston Harbor Entrance.

The remaining stations occupied are scattered along the Atlantic, Pacific, and Gulf coasts, with a few stations in Alaskan waters. Long series of observations are also being obtained at Chesapeake and Barnegat lightships.

U. S. Coast and Geodetic Survey,
Washington, D. C.

OCEANOGRAPHIC RESEARCH AT THE SCRIPPS INSTITUTION DURING APRIL 1934 TO APRIL 1935

T. Wayland Vaughan

Improvements--The improvements that were being made in the Institution's boat Scripps mentioned in the report on the work of the Scripps Institution for last year were not finished so soon as was expected, but they have now been completed and they have rendered the boat more efficient than was at first expected. The old 75-horse-power gasoline engine has been replaced by a 120-horse-power, 6-cylinder Diesel engine, and an auxiliary power- and light-system of the latest design, also operated by a Diesel engine, has been installed. The boat has been equipped with a new oceanographic winch capable of obtaining temperatures and water-samples to a depth of 6000 meters and of dredging to a depth of 1500 meters. The living quarters have been remodelled and the laboratory has been re-equipped for chemical work and the handling of bacteriological and other samples.

The instrumental equipment purchased during the year comprises four Nansen water-bottles and six protected and unprotected Richter and Wiese reversing-thermometers. These instruments, when added to those already on the boat, make the equipment of the Scripps adequate for the different kinds of work contemplated.

Expeditions and oceanographic data--Because of the delay in completing the replacements on and renovations of the Scripps, the boat was not available for use during the period to which this report applies. The only expedition at sea in which the Institution participated was in the work of the U.S.S. Bushnell. The United States Navy gave permission for Roger Revelle, one of the research assistants on the staff of the Institution, to join the Bushnell at Seattle on July 19 and to proceed aboard it to Dutch Harbor in the Aleutian Islands. Between August 18 and 27 the Bushnell occupied 18 stations between Adak, Aleutian Islands, and Pearl Harbor in the Hawaiian Islands. The report on the activities of the Navy to be submitted to this meeting by the Hydrographer of the Navy will give fuller information regarding the work of the Bushnell. Further notes will be made in this report in the account of the work in chemistry at the Scripps Institution during the past year.

Table 1 summarizes the oceanographic data received at the Scripps Institution during the year.

Water-samples and data received from the U.S.S. Hannibal were taken in the Gulf of Panama and off the coast of Costa Rica. Water-samples and data were collected by the Velero III along and off the west coast of South America in February, 1934. In 1935 the Velero III obtained about 150 surface-temperature records and water-samples between Cape San Lucas, Lower California, and Independencia Bay, Peru (14° 14' S). On its southbound voyage a series of collections was made

Table 1--Number of observations of sea-temperatures, salinities, and meteorological conditions received at the Scripps Institution, March 15, 1934, to March 15, 1935

Group	Station or ship	Salinity	Temperature	Wind	Air temperature	Remarks
A	Seven shore-stations, La Jolla to Scotch Cap, Alaska	2835(a)	2835(c)	2105	365	Barograms, daily wet- and dry-bulb readings, precipitation, and daily temperature and salinity at 5 meters at Scripps Pier
	U.S. Lighthouse tenders Sequoia, Lupine	120(a)	1258(c)	1258	1258	Sea-water thermograms for all coastal trips of Lupine
	Rose	96(a)	219(c)	219	....	
	Panama Pacific steamers Virginia, Pennsylvania, California	....	....	....	....	Sea-water thermograms
	Grace Line, Valparaiso to Central American ports	....	2470(c)	84	84	
	La Punta, Callao	....	84(c)	84	84	
	Totals	3050(a)	6866	3666	4177	
B	Florida Keys	4(b)	4(c)			Notes: (a) = determined by specific gravity; (b) = determined by chlorine titration; (c) = at surface; (d) = serial; (e) = surface and subsurface; (f) = aquarium samples
	U.S.C.G.S.S. Guide (California Coast)	80(b)	80(d)			
	U.S.C.G.S.S. Pioneer (California Coast)	51(b)	51(d)			
	Dr. H. S. Ladd, Fiji Islands	56(b)	53(e)			
	Yacht Velero III (Eastern Pacific equatorial waters)	266(b)	266(c,d)			
	U.S.S. Bushnell (Alaska to Hawaiian Islands)	308(b)	308(d)			
	U.S.S. Hannibal, 1934	317(b)	317(d)			
	Miscellaneous	32(b)	32(f)			
	Totals	1114(b)	1111			

on a line from Cape San Lucas to the Galapagos Islands, and from there into Guayaquil. A line was then run southward to a point about 300 miles off the coast of Peru (10° 30' S and 82° 00' W). From this point a line of five vertical series down to about 500 meters, or to the bottom, was run into Callao, Peru. Further collections of surface-observations were made as far south as Independencia Bay to Panama and finally to Cape San Lucas. The subsurface observations across the Peru Current consist of about 40 water-samples and temperature-observations.

Physical oceanography and marine meteorology--Dr. George F. McEwen has continued summarizing reports on sea-surface temperatures and other oceanographic data, and he prepared for publication a series of sea-surface temperature records furnished for a seven-year series by the Grace Line between Central American ports and Valparaiso, Chile. The data were averaged and plotted on charts by months and one-degree quadrangles. The data for serial sections at sea, temperature and salinity, for southern California waters are being typed on cards in preparation for the discussion of the dynamical oceanography of the region within which the data are taken.

As an aid in studying local movements of the water, particularly near shore, a pendulum type of current-meter to record two components of the velocity has been designed for use on the sea-bottom. Not all of the difficulties of operation of this meter have been overcome, but the outlook is encouraging for the construction of such a meter to weigh about 75 pounds and to cost about $100. Dr. McEwen has made a study of the effect of the high ocean-waves which have been common along the coast of southern California during the past year with reference to their destructive effect on the shore-line, and he has prepared an illustrated paper which will be published at an early date in the Journal, "Shore and Beach."

During the year much attention was devoted to various meteorological subjects among which will be mentioned the forecast of mean monthly air and sea-surface temperatures which were made for the southern California coast region at intervals of three months, accompanied by a general

statement for the six-months' periods, January to June and June to December. Investigations of possible bases of long-range forecasting of seasonal precipitation, including studies of cycles, correlation with ocean-temperatures, and cycle-factors, were continued. A critical study was made of the application of statistical methods to determine the maximum flood to be expected in a given interval, this study being carried out for the Subcommittee on Statistical Methods as Applied to Hydrology under the Section of Hydrology of the American Geophysical Union. Another investigation was that of variation in precipitation indicated by rain-gages distributed over a watershed and the error in measuring the total amount of water supplied to the watershed. This investigation was in collaboration with W. C. Lowdermilk of the United States Department of the Interior in his studies of surface-erosion.

Other investigations dealt with statistical methods as applied to oceanographic data in general and to biological subjects in particular.

N. W. Cummings conducted experiments at San Bernardino to test a method for using a Burt phototube in an integrating pyrheliometer, and a design for such a pyrheliometer adapted for use on board the Scripps was perfected.

Burt Richardson prepared for publication in the Monthly Weather Review a paper entitled "Solar radiation at the Scripps Institution of Oceanography, La Jolla, California, 1926-34."

A report on the very detailed survey by F. P. Shepard of the submarine canyon off the waterfront of the Institution's property will be given by Dr. Shepard before this meeting of the Section of Oceanography. A model of this canyon has been constructed at the Blackstone Studios, Rochester, New York. Its dimensions are 18 inches by 45 inches, the vertical and horizontal scale being the same. The price of the model f.o.b. Rochester is $25.00. A model has been purchased by the Scripps Institution and is satisfactory in all respects.

T. W. Vaughan prepared for presentation at the meeting of the Consejo Oceanográfico Ibero-Americano, to be held in April 1935, a paper entitled "The status of the oceanographic exploration of that part of the Pacific between latitude 10° north and 41° south and east of longitude 120° west." This paper is illustrated by a chart which shows the position of all of the stations occupied for the determination of subsurface temperatures and salinity within the area considered, and a rather full bibliography is included. He has also submitted for publication by the Carnegie Institution of Washington the manuscript of a paper entitled "Current-measurements along the Florida coral-reef tract."

R. H. Fleming has completed a study of the data obtained on board the U.S.S. Hannibal in the Gulf of Panama and off the coast of Costa Rica in 1933, and he has prepared a manuscript report entitled "Oceanographic studies in the Central American Pacific." This manuscript includes studies of the chemical features and of the circulation of the water.

Chemical investigations--The work on chemistry at the Institution during the past year has continued in charge of E. G. Moberg. The Section of Chemistry, as in the past, has accumulated information intended to advance knowledge of the circulation, of certain geological processes, and of the biological environment in the sea. Accordingly, determinations of the chlorinity, the hydrogen-ion concentration, and the phosphate, silicate, and titrable base-content of the sea-water collected at the Institution's pier have been made at regular intervals weekly. A number of samples taken at the pier have been analyzed for calcium and borates.

An especially interesting set of 56 water-samples collected in the Fiji Islands by H. S. Ladd and J. Edward Hoffmeister has been received and partly analyzed. A part of the purpose of the study of these samples was to ascertain their capacity to retain calcium carbonate in solution or to dissolve calcium carbonate. Consequently, the samples have been analyzed for chloride, titrable base, and calcium. The salinity of the samples as indicated by the chlorinity ranged from nearly zero to 35 per mille, and a similar, though not always parallel, range was found in the titrable base and calcium-content.

Another interesting set of samples was obtained by Roger Revelle on the U.S.S. Bushnell between the Aleutian Islands and Honolulu. These samples will be analyzed for chlorinity, titrable base, and calcium, mainly to obtain additional information relative to certain differences in the chemistry of the Pacific and the Atlantic ocean-waters. Mr. Revelle, while on board the Bushnell, determined the oxygen-content of the water at several stations and at various depths, thus connecting with the observations made by the Carnegie south of latitude 35° north, and with those made by the University of Washington near the Aleutian Islands.

It became necessary for H. W. Graham and E. G. Moberg to revise the report on chemistry for the Carnegie Expedition because after those reports were originally prepared three years ago a considerable amount of information dealing with the chemistry of sea-water has been published.

Microbiology--C. E. ZoBell has shown that bacteria have a great capacity to affect in marine bottom-deposits the O/R potentials which are of biological, geological, and chemical significance. Potentials of E_h -0.1 to -0.3 volt are common in bottom-deposits, some muds being as reducing as -0.52 volt. The optimum for bacterial nitrification was found to be E_h +0.30 to +0.55 volt (J. Bact., v. 29, p. 78, 1935). Multiplication, proteolysis, carbohydrate-fermentation, ammonification, and nitrification in marine bacteria have been observed at 0° to -2° C, which indicates that bacteria are functional at the low temperatures encountered in the deep sea (Q. Rev. Biol., v. 9, p. 460, 1934). ZoBell and Mrs. Catharine B. Feltham have described three classes of urea-splitting bacteria from the sea which are active at sub-zero temperatures (Science, v. 81, pp. 234-236, 1935). Miss Helen M. Mathews found that, while bacteria which denitrify under favorable conditions occur abundantly throughout the sea, oceanographic data reveal that these conditions are infrequent. Concentration of nitrates, nitrites, and organic matter, temperature, oxygen-tension, and O/R potentials were considered as controlling factors. ZoBell and Wells have described the pathology and a successful hyperthermic therapeutic treatment of an infectious dermatitis of Fundulus parvipinnis (J. Infect. Dis., v. 55, p. 299, 1934). Study of the tolerance of that species indicates that certain bactericidal baths may have a prophylactic value (Proc. Soc. Exper. Biol. and Med., v. 32, p. 704, 1935). The application of statistical methods to observations on the vertical, diurnal, and seasonal distribution of bacteria in the sea show no evidence of a lethal action of sunlight, as claimed by others (with G. F. McEwen, in Biol. Bull., v. 68, p. 93, 1935). An improved bacteriological water-sampling bottle has been perfected. D. Q. Anderson has initiated a series of experiments to ascertain the nature and extent of the decomposition of various natural celluloses, sulphydryl compounds, chitins, and other organic matter in marine muds. ZoBell has shown that pure bacteria-free cultures of Nitzschia closterium and other marine phytoplankton assimilate ammonium. These organisms reduce nitrates to nitrites and probably preferentially assimilate the latter.

Phytoplankton--W. E. Allen has completed an examination of the plankton diatoms and dinoflagellates contained in the collections made by R. H. Fleming from the U.S.S. Hannibal in the Gulf of Panama and vicinity in 1933, and of the collections made by Roger Revelle on the U.S.S. Bushnell between the Aleutian Islands and the Hawaiian Islands in 1934. The examinations and computations for the phytoplankton collected from the Institution's boat Scripps during the years 1929, 1931, and 1932 have also been finished. The report on the daily occurrence of diatoms at southern California piers for the decade 1919-29 has been partially prepared. The calculations of daily abundance and most of the tables for the dinoflagellates for the same decade have been finished. The microscopic work and primary calculations for daily collections from the pier for 1930 have been finished and some of the microscopic work for the 1931 collections has been done. Special attention has been given to advancing the microscopic work beyond 1929 because, for the later years, more complementary information on chemical conditions and bacteriology is available. The studies of fouling organisms at the Institution's pier has been continued.

Easter E. Cupp has completed a preliminary manuscript on the phytoplankton samples collected at Scotch Cap, Aleutian Islands, over a period of seven years, August 1, 1926, to June 30, 1933. A statistical analysis of measurements of a large number of individuals of a variety of Nitzschia seriata Cleve collected over a wide geographical range has been made and a report nearly completed. Some attention has been paid to centrifuge methods of phytoplankton analysis and a number of samples from the Institution's pier have been examined. Collections from other localities for treatment with centrifuge are also available. Culture of diatoms has been initiated and progress made. Two species of the genus Nitzschia have been isolated and preliminary experiments carried on in connection with work by D. L. Fox and C. E. ZoBell.

Foraminifera and an Anthomedusa--E. H. Myers, who last year reported on the results of his investigation of the life-cycle of Patellina corrugata, has extended his investigation to Spirillina vivipara, in which the cycle, in all respects, conforms to that described for Patellina. One of the results of this work is to show that the nuclei of the foraminifera are derived by mitosis and not from chromidia. The study of the flagellates which occur at definite stages in the life-cycle of certain foraminifera, such as certain species of Discorbis and Tretomphalus bulloides, has been resumed in the hope that it may be definitely ascertained whether these so-called zoospores are or are not gametes. Myers has also investigated in cultures over a period of two years a Pacific Coast species of the Anthomedusa, Cladonema. A mutation of this species has been found in which the absence of the second whorl of tentacles in the hydroid results in an altered symmetry of the radial canal system in the medusa.

M. L. Natland has continued his study of the ecologic relations of the foraminifera in the Gulf of Catalina, and has nearly completed a report on those found in the waters adjacent to and offshore from La Jolla.

Zooplankton--Martin W. Johnson has completely worked out the life-histories of two species of copepods, Labidocera trispinosa and L. lollae, on living material collected at the Institution's pier. The completion of these two life-histories brings the number of known life-histories of the Calanoids, the most important group of the pelagic copepods, to a total of eighteen. Johnson had previously worked out the life-histories of Tortanus discaudatus and Ellabidocera. During the year he has also studied the samples of zooplankton collected by Roger Revelle aboard the United States Coast and Geodetic Survey steamer Pioneer off Pt. Arguello in 1933, when fifteen collections distributed over six stations were made. The decrease in the quantity of the zooplankton is quite uniform below the surface and appears to be correlated with depth irrespective of the minimum oxygen-layer which is about 350 to 450 fathoms below the surface. The Pioneer collections have yielded material of interest in studies of both the geographic distribution and the life-histories of copepods. Johnson has continued his studies of the seasonal migration of the wood borer Limnoria lignorum (Rathke) on material and data collected at Friday Harbor. He has devoted some attention to the fouling organisms that have attached themselves inside the lead pipes of the salt-water system at the Institution.

Biology of fishes--F. B. Sumner has continued his studies of the protective value of color changes in fishes. Several thousand fishes of a small species, Gambusia patruelis, were kept for some weeks in black and white aquaria, respectively, until the dark and pale appearance thus produced had become to some extent fixed. They were then transferred in equal numbers to one of two large wooden tanks (one black, the other pale gray), and exposed to the attacks of fish-eating birds. Galapagos penguins and a small night-heron were used for this purpose. In every experiment a much greater proportion of those fishes were eaten which did not harmonize in shade with the background. Similar experiments are being conducted with larger fishes as predators, and with equally clear-cut results.

In cooperation with D. L. Fox, Dr. Sumner has continued experiments upon the source of the yellow pigment (xanthophyll) in fishes, and upon the influence of colored backgrounds in affecting the amount of this. Fundulus parvipinnis was found to increase its total xanthophyll-content greatly upon a diet which was rich in this substance, but likewise showed an increase more than half as great when the diet was rich in carotene but contained no significant amount of xanthophyll. The conversion of carotene into xanthophyll by animals has not hitherto been observed. Another fish, Girella nigricans, however, lost a large proportion of its xanthophyll under laboratory conditions regardless of the diet employed. This loss was far more rapid in white tanks than in yellow, black, or gray ones.

N. A. Wells, partly in collaboration with F. B. Sumner, has made studies of the metabolic rate of fishes as influenced by present or past exposures to various temperatures. Several series of experiments with gobies confirmed Wells' previous conclusions for Fundulus that fishes exposed for some weeks to relatively high temperatures showed, when transferred to a lower temperature, a markedly lower metabolic rate than fishes which had been kept continuously at lower temperatures. Tests of susceptibility to an anesthetic (urethane) showed that this varied directly with metabolic rate, as based on oxygen-determinations. Other studies by Wells included the selective action of germicides on Fundulus, the temperature-tolerance of certain fishes, and the physical and chemical factors involved in maintaining fresh-water aquaria.

P. S. Barnhart has completed the manuscript and illustrations for a rather large volume entitled "Marine fishes of southern California," which has been submitted to the University of California Press for publication as one of the Institution's technical bulletins.

Physiology of marine organisms--It has already been stated that D. L. Fox, who has charge of the Institution's physiological laboratory, is cooperating with F. B. Sumner in a study of the carotenoid pigments in marine fishes. A long paper dealing with the habitat and food of the California sea-mussel, Mytilus californianus, by D. L. Fox, G. W. Marks, Florence O. Austin, and Horace Buley, has been completed and submitted for publication as one of the Institution's technical bulletins. Preliminary studies have been made jointly with Mrs. Lois Sorkness, a student, of the inactivation and coagulation by heat of the enzyme emulsin. Certain dyes which prevent the heat coagulation of typical proteins do not prevent the heat inactivation of the enzyme. Investigations of the influence of heavy water upon hydrolyzing and desmolyzing enzymes from marine invertebrates, the growth of isolated cultures of marine diatoms and marine fungi, and the fertilization of ova, the development of the embryos, and the metamorphosis of the larvae, of a marine ascidian, have been undertaken. G. W. Marks has investigated the copper content and the

copper tolerance of some Pacific Coast marine mollusks. The upper limit of tolerance of nine different forms is less than 0.20 mg Cu/kg sea-water, but the rock-cockle, Paphia staminea, shows a striking tolerance, suffering no ill effects from copper salts dissolved to the limit of solubility in sea-water. The copper content of sea-water off La Jolla is 0.001 mg/kg. Investigations into the relationship between age (size) and total body copper in both Mytilus californianus and Ischnochiton conspicuus have been begun. Marks has observed that catalases from a number of marine plants and animals are strikingly similar in chemical behavior. A considerable number and variety of chemical and biochemical compounds are being studied with reference to their influence on the rate and inactivation of marine catalases. One of the most remarkable of these is glutathione, the investigation of which is being continued.

Marine bottom-deposits--In the report for last year it was stated that two rather large undertakings had been brought to completion. But it was soon recognized that additional work on each of them was needed. However, E. M. Thorp has now completed a large manuscript entitled "Calcareous shallow-water marine deposits of Florida and the Bahamas," which has been transmitted to the Carnegie Institution of Washington for publication as one of the reports on work conducted in connection with the Marine Biological Laboratory at Tortugas, Florida. A preliminary abstract of this paper has been published in the December issue of the Journal of Sedimentary Petrology. Thorp has also completed a short report on some Red Sea bottom-samples collected in the vicinity of the Marine Biological Station at Ghardaqa, Red Sea District, and he has nearly completed a report on marine bottom-samples collected by Paul Galtsoff during his survey of the Pearl and Hermes Reef, Midway Islands. Roger Revelle has spent nearly another year on the study of the marine bottom-samples collected by the Carnegie during her work in the Pacific. An abstract of some of the results from this study are given in an article in the April, 1935, issue of the Journal of Sedimentary Petrology. It is expected that the manuscript will be in form for publication by the end of the current spring. The studies of oxidation and reduction in the ocean by C. E. ZoBell have been continued and have been mentioned in the notes on the work in microbiology for the year.

Robley D. Evans, assisted by Arthur Kip, continued his study of radioactive substances in waters in the vicinity of the Scripps Institution and in some of the organisms.

Conclusion--The foregoing report shows that the members of the staff of the Scripps Institution have not only been active during the year but have a considerable number of accomplishments to their credit. The number of papers published during the year was 49, the number in press is 16, the number submitted for publication is 12, and 7 additional papers are ready to be submitted. A number of the published papers were written several years ago and were published during the past twelve months.

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BED-ROCK FROM THE CONTINENTAL MARGIN ON GEORGES BANK

H. C. Stetson

(Contribution No. 76 from the Woods Hole Oceanographic Institution)

Within the last few years, the United States Coast and Geodetic Survey has recharted Georges Bank for the benefit of the fishing industry. Sonic methods were used which permitted numerous closely-spaced soundings. During the course of this survey, many valleys were found, cutting the southern edge of the bank, which here, of course, is coincident with the edge of the continental shelf. The floors of these valleys range from about 1200 feet to more than 8000 feet below the present sea-level. The charts indicate that similar valleys cut the continental margin in various places between the Grand Banks and Cape Hatteras. Two off the Maryland coast have recently been charted in enough detail to indicate that they are of the same type. Although this study is concerned specifically with the canyons of Georges Bank, it must be borne in mind that the conditions which produced them have affected a large portion of our eastern continental slope.

Soundings are numerous enough to permit the drawing of accurate contour-maps of these valleys, which has been done by F. P. Shepard, who reached the conclusion that their configuration indicates that they are fluviatile in origin (Canyons off the New England Coast, Amer. J. Sci., v. 27, pp. 24-36, 1934). It is not necessary to appeal, as he does, to some preexisting river with its origin back in the hinterland to provide the means for cutting these canyons, though in

the case of the Hudson submarine channel, such a valley can still be traced. Starting from the face of a scarp, canyons of the order of magnitude represented here can grow by headward erosion in any plateau-region, due to ground-water sapping. Many formed by this process are well shown on the United States Geological Survey's topographic sheet of the Bright Angel Quadrangle, Coconino County, Arizona. Elevation of the continental margin would provide an ideal scarp for erosion of this type to take place.

Fault-troughs and submarine currents have been appealed to as producers of these gorges. However, Shepard's contour-maps are based on a sufficient number of soundings to give a fairly good idea of their configuration, which is decidedly not that of a fault-trough or rift-valley. In regard to the second hypothesis, it is almost impossible to conceive of hydrographic conditions which could produce submarine currents powerful enough to cut such gashes. If, however, such a current could be produced, it would be equally difficult to imagine it restricted to so limited a channel and flowing at right-angles to the coast-line.

The soundings indicate that in places the slope of the valley-walls is considerably above the angle of repose for unconsolidated material, and that, therefore, they must consist of rock. Hence, these gashes afford an opportunity of getting at the bed-rock of which the edge of the continent is composed, and, should it prove to be fossiliferous, of fixing the maximum time-limit for the cutting of these canyons. Everywhere else, the rocks composing the shelf are mantled with a veneer of recent sediment too thick to be penetrated. Numerous fragments containing fossils have been found on Georges Bank before, but none had ever been taken in place.

Accordingly, the Woods Hole Oceanographic Institution, in August 1934, sent the ketch Atlantis on a dredging trip to three of the newly charted canyons cutting the southern edge of Georges Bank between 67° 38' and 68° 11' west longitude. A special dredge of heavy construction was used. In four successful tows, material was actually broken from the cliffs of the walls of the canyons. In six other cases, glacial debris was obtained. As the dredge was of the drag-type, only the upper and lower limits of each uphill tow could be recorded. It is not possible, therefore, to fix the exact depth at which any single formation was encountered. The middle and upper parts of these valleys were found to have the steepest walls and yielded the best results.

Lloyd W. Stephenson is working on the megafossils (molluscs and echinoderms) which were found in a poorly sorted, coarse sandstone obtained between 596 and 480 meters below the surface in the westernmost of the three major canyons, north latitude 40° 24' 30" and west longitude 68° 07' 30". He reports that the evidence indicates a stratigraphic position for this sandstone, "either in the upper part of the Exogyra ponderosa zone or in the lower part of the Exogyra costata zone (= Exogyra cancellata zone). In terms of the New Jersey and Maryland Upper Cretaceous section, this would correspond in age to the upper part of the Matawan group or the lower part of the Monmouth group. In terms of the standard European time section, it would be Upper Campanian, or possibly Lower Maestrichtian."

J. A. Cushman is working on the foraminifera occurring in the clays and greensands. In two separate instances, in a greensand he has found the fauna to be the exact equivalent of that from the Navarro formation. This places it in the Upper Selma Chalk of the Upper Cretaceous. This formation was first encountered in the middle canyon of the three, between 600 and 530 meters of water, north latitude 40° 20' 30" and west longitude 67° 51' 15", and again in the easternmost canyon, between 640 and 512 meters depth, north latitude 40° 27' and west longitude 67° 39' 30". In the three tows mentioned above, in addition to the greensand, a massive green clay was obtained. This outcrops again in the easternmost canyon between 458 and 452 meters depth, north latitude 40° 29' 45" and west longitude 67° 41' 40". From this clay comes an assemblage of foraminifera, which in general resembles that occurring in the Miocene of Maryland. There is a new species of Plectofrondicularia, whose nearest relatives are found in the Miocene of California, but, as this is a new form, it cannot be assumed, as yet, that its range is likewise restricted. In general, the assemblage seems to indicate a deep-water environment, whose fossils are but little known, as the Tertiary fauna of the Atlantic Coastal Plain is a shallow-water one. As further evidence in favor of the Miocene age of this clay, we may cite the fact that none of the recent forms from the surface sediments of the Gulf of Maine, or nearby continental shelf, is present. There is, therefore, the distinct possibility that when this fauna has been further studied it can be assigned definitely to the Miocene.

Glacial material was encountered on every tow above 450-meter depth to the rim of the canyon. In two instances, it was found below this point, reaching to 565 meters in the westernmost of the canyons, north latitude 40° 18' and west longitude 68° 07', and to 572 meters, north latitude 40° 20' 50" and west longitude 67° 50' 40". Most of the tows which yielded glacial debris mixed with recent mud were taken from the walls of the valleys near their mouths, where the slopes are not as steep as in the middle and upper sections.

Numerous cores between three and four feet long were taken from the valley-floors. Many of them consist of a true clay, dissimilar in mechanical composition to the sediment at equal depths on the continental slope, which contains a much higher percentage of silt and sand. However, the foraminifera from these cores are all recent forms, though many of them are not living on the surface-sediments at present.

Bare slopes were encountered only in the middle and upper portions of the canyons, where the walls appear to have the steepest gradient. Elsewhere, as noted above, on the sides as well as on the valley-bottoms, the older rocks are blanketed by layers of recent sediment too thick to be penetrated.

The study is not yet complete, but at the present writing we may draw the following conclusions:

(1) Georges Bank is fundamentally an extension of the Atlantic Coastal Plain, with a covering of glacial debris.

(2) If these canyons are fluviatile in origin, the fossils contained in the samples broken from their cliffs show definitely that part of our eastern seaboard has been involved in tectonic movements comprising an elevation and submergence of more than 8000 feet since the Upper Cretaceous. Furthermore, this time-interval will be still further restricted if the suspected Miocene age of other formations can be substantiated.

(3) That portion of the Atlantic Coastal Plain which is now above sea-level shows little evidence of any orogenic movements. If we may assume a like condition for the submerged portion, the movement which elevated the continental margin must have been in the form of a block-uplift, or a simple tilt, with the fulcrum at, or west of, the Piedmont boundary.

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SEASONAL VARIATION IN NORTH ATLANTIC SURFACE-TEMPERATURES

W. F. McDonald

Meteorologists and oceanographers are alike interested in the variations of ocean-surface temperature. The passage of the seasons is attended by changes in water-temperatures that, in general, differ only in amplitude from the similar seasonal fluctuations in atmospheric temperature; however, the conservative properties of the ocean-surface and the influence of currents cause interesting variations in temperature sequences which merit special attention.

The annual range of surface-water temperatures in the North Atlantic Ocean has been charted by Schott (Geographie des Atlantischen Ozeans, 1926, Tafel XI). In the British "Marine Observer" for 1926 (Met. Office, London) there appeared a series of 12 monthly charts showing by 2° rectangles the averages of surface-water temperature for most of the North Atlantic Ocean, based upon 63 years' observations (1855 to 1917).

The annual temperature-range, computed from the complete monthly normals given on the British charts, is shown herewith as Figure 1. Schott states (p. 136) that his chart is based upon the differences between February and August mean temperatures; apparently he did not make a complete examination of maxima and minima with regard to all months. In many squares especially at low latitudes the annual maxima and minima occur in other months than August and February but in general Figure 1 confirms Schott's chart.

Continental climate is evidently a predominant factor in the areas of large annual variation in sea-surface temperature. The amplitude of the annual fluctuation in sea-temperature is greatest from Hatteras to Labrador, where the prevailing winds bring to bear upon the sea-surface the wide fluctuations in air-temperature which characterize the changes of season on the North American Continent. Similarly, the influence of the European continental shores is discovered in an increase of seasonal range in sea-surface temperatures near the French coast. The localized area of relatively large annual range between Cape Blanco and Cape Verde is also, in part at least, explainable as the result of continental influence on wind-direction, causing the trade-winds in that area to vary considerably with seasonal temperature-changes over the Saharan region.

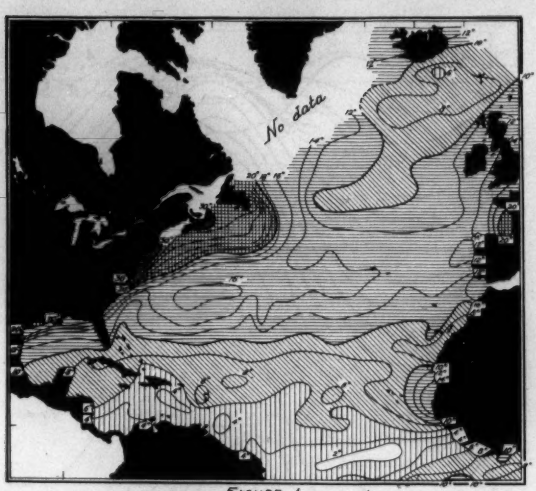

FIGURE 1
ANNUAL RANGE OF TEMPERATURES

The areas of small annual range in sea-temperature are two in number; the most extensive is the tropical belt, a minor part of which, on the heat equator, has an annual amplitude less than 2° F. A lesser, but in some respects more interesting, region of relatively high temperature-stability lies between the British Isles and Iceland, where, notwithstanding the much larger range in air-temperatures, the sea-surface undergoes an average annual change of only 6° to 8° F.

Clearly, in this latter case, we have an evidence of the stabilizing effects of a persistent surface-drift. The driving force for currents in the sea-area at these higher latitudes is the atmospheric circulation around the procession of low-pressure centers that pass through the region between the British Isles and Cape Farewell. In winter these cyclones are most vigorous, and their effect is then to intensify the set of warm currents northward; this to a degree counteracts the cooling influence of the winter season upon the ocean-surface near Iceland. In summer, the atmospheric circulation is weaker and the sea-surface in the extreme northeastern Atlantic then tends to assume the temperature-condition proper to the season and latitude. Warm-season temperatures are thus maintained in good relation to the latitude, but minima are abnormally raised with the result that the annual range of temperature is greatly diminished.

The stabilizing effect of the Florida Current very definitely appears along the American coast south of Cape Hatteras, where the lines of equal amplitude are bent strongly northward across the parallels of latitude. At some other places, notably in the area 25° to 30° north and 45° to 55° west, groups of lines assume modified contours strongly suggestive of localized drift-influences. Currents of set and intensity proportionate to contours of temperature-lines are, however, not in all cases established upon available current-charts, so the explanation of many of these variations is obscure.

Figure 1 indicates clearly that the belt of greatest annual change in temperature, taking into consideration the whole breadth of the North Atlantic, lies between 35° and 45° north latitude, throughout which the diminishing influence of the strong range developed near the American coast seems to be carried eastward all the way to Europe.

This is brought out in another way in Figure 2, which represents the annual march of average monthly temperatures computed by 2° strips of latitude extending from coast to coast across the Atlantic. The maximum annual range in these curves is about 18°, in that for 42° to 44° north.

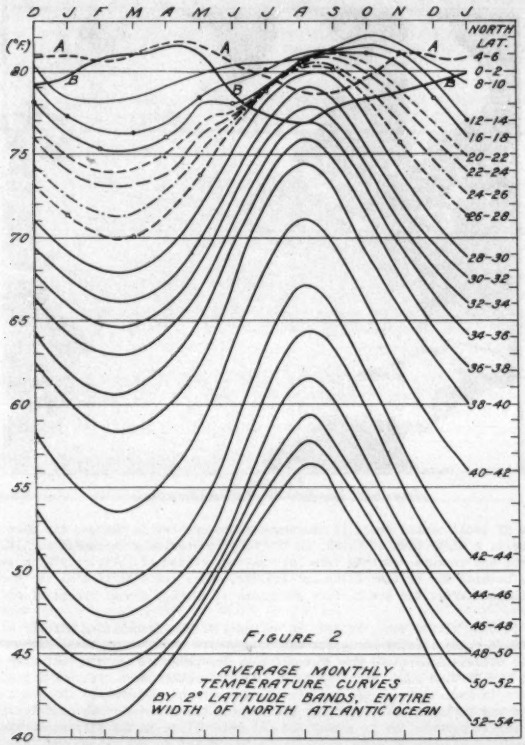

FIGURE 2

AVERAGE MONTHLY TEMPERATURE CURVES BY 2° LATITUDE BANDS, ENTIRE WIDTH OF NORTH ATLANTIC OCEAN

Figure 2 reveals other points of interest. The region in which average temperatures change most rapidly from latitude to latitude is between 38° and 44° north. The curves for higher and lower latitudes lie much closer together, but in this region of largest change the average annual temperature decreases northward about 2° F per degree of latitude, as compared with a rate of about 0°5 above the 50th parallel, and a rate of only 0°2 F at latitudes below the 20th parallel.

The great alteration in form of the temperature-curves at latitudes below the Tropic of Cancer shows the progressive effect of two variables. The first is the change in shape of the curve of solar radiation from the simple sine-form of higher latitudes to a curve at low latitudes, having double maxima which tend to produce double-phase effects in the water-temperatures. This is exemplified by temperature curve AAA for the latitude band from 4° to 6° north (Fig. 2). The second influence, which operates within a few degrees north of the equator but has no general effect above 6° to 8° north, is the strong drift across the equator from the South Atlantic, which brings the influence of the reversed order of seasons characterizing southern latitudes into play upon the average temperature-history of those North Atlantic waters just across the equator. Temperature curve BBB shows the extreme degree of the southern latitude influence. (See also paper by Church on Surface-temperatures on the New York to Cape Sao Roque steamship-route, Trans. Amer. Geophys. Union, 15th Annual Meeting, pp. 204-208, 1934.)

Between the 30th and 10th parallels, however, the most noticeable change of form in the

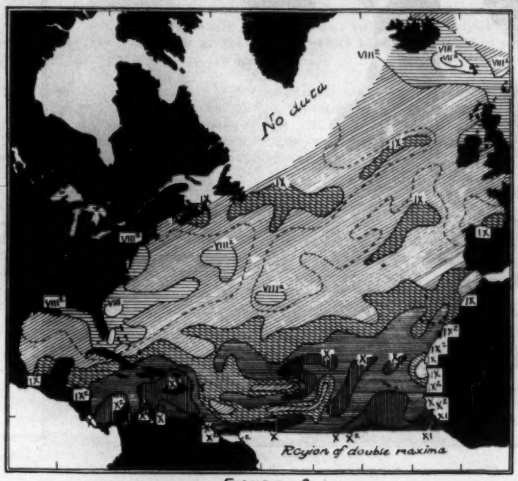

FIGURE 3
EPOCH OF MAXIMUM TEMPERATURES

[Explanation--Time-lines indicate nearest half-month: VIII, IX, X, etc., stand for the first of August, September, October, etc., and $VIII^2$, IX^2, X^2, etc., represent the middle of these months. The dotted lines in the field for the latter half of August ($VIII^2$ to IX) indicate the approximate separation of that half-month into weekly periods.]

temperature-curves is a retardation of the time of maximum, which is shifted from latter August to middle October. To study more fully the details of this displacement of maxima a chart (Fig. 3) has been prepared, upon which is indicated the epoch of maximum temperature carefully estimated to the nearest half-month for each 2° square with a full temperature-history.

Figure 3 reveals some unexpected irregularities in the time of occurrence of maximum temperatures. The large retardation that characterized the maxima of average curves in Figure 2 for latitude bands between 8° and 20° is shown by the detail of Figure 3 to be due to a number of areas where retardation goes late into October and, in some spots, beyond the first of November. But what is particularly surprising is to find in this region of generally late maxima localized areas in which the epoch of maximum temperature comes as early as August. Variations of as much as ten weeks occur within a distance of two or three hundred miles at places between 12° and 18° north.

At higher latitudes the contrast of dates is less sharp, but the earliest maxima appear there in two widely separate places, one in the Florida Current and the other off southeastern Iceland.

A parallel study was made of the epochs at which average minimum temperatures occur. In general, the times of minima are not so sharply marked as the maxima, and for that reason it was much more difficult to secure a clean-cut chart of detailed isochronal lines representing computed dates of minima. In many 2° squares, the same figure (to whole Fahrenheit degree) for average minimum temperature was recorded in three or four of the months of the year. By adopting the last month in each case as the criterion for a chart, and with rather liberal smoothing of local irregularities, the generalized lines of Figure 4 are obtained.

Figure 4 therefore roughly represents in each area the month from which the seasonal rise of temperatures may be regarded as beginning. It shows an extreme variation from January to April, with a notably irregular pattern of lines having little apparent relation to latitude.

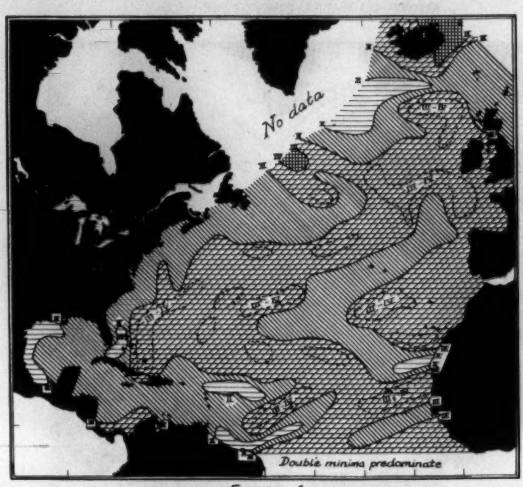

FIGURE 4
EPOCH OF INCEPTION OF RISING TEMPERATURES

[Explanation--Time-lines indicate months: February = II, April = IV, etc. Earliest epoch of rising temperature, in January, is indicated by horizontal shading (under II). Diagonal shading (II-III) indicates rise in temperature, beginning in February, and area with latest inception of rising temperature, in April, is indicated by heavy cross-hatching within the IV-line. Dotted lines in the area between III and IV show limited regions in which temperature rise normally begins in March but is often delayed until April.]

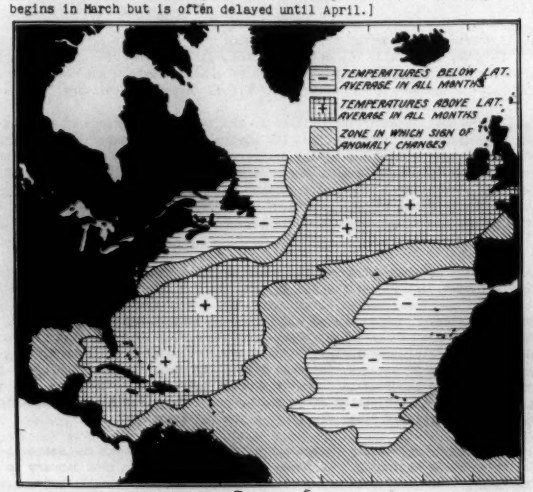
TEMPERATURES BELOW LAT. AVERAGE IN ALL MONTHS
TEMPERATURES ABOVE LAT. AVERAGE IN ALL MONTHS
ZONE IN WHICH SIGN OF ANOMALY CHANGES

FIGURE 5
ANNUAL SUMMARY OF TEMPERATURE DEPARTURES FROM LATITUDE NORMALS

Comparing the two isochronal charts (Figs. 3 and 4) a common characteristic can be seen. The general trend of lines is predominantly from southwest to northeast. Apart from this, and a slight tendency to earlier occurrence of the charted events along the American side of the ocean, there is little similarity between the two charts.

No obvious theory of causation can be offered to account for the patterns of isochronal lines. The major drift-lines from Florida to the northeastern Atlantic are suggested, however, by the general trend of time-lines on these charts. It seems probable that complex interrelations of surface-drift and accompanying tendencies to upwelling or to repetition of eddy motions in similar space patterns may, at least in part, underlie the diversity of the areas outlined on these charts.

At places where surface-drift goes strongly across the latitude, the arrival of waters from a northern origin will operate to produce a negative abnormality, whereas transport from southerly origins is often productive of local temperatures higher than average for the latitude. Of course, other influences, such as upwelling or abnormal cooling through the agency of cold continental air-masses, doubtless play a part in causation of latitudinal anomalies of surface-temperature, but the general ocean-wide picture of anomalies appears to be explainable in the major sense as a result of surface-drift.

To give form to this idea that the major drifts should reveal themselves as temperature-anomalies, the monthly normal temperatures by 2° squares were compared with the latitude average and the local deviations charted for each month. The mean value for each band of latitude, 2° in width and extending entirely across the Atlantic, was used as the base of reference for local values in that band. (See Figure 2 for graphic presentation of latitude average values.) Where the averages by 2° rectangles were not published for the full breadth of the ocean (as was the case at higher latitudes), it was of course impossible to obtain a complete latitude average; hence the local anomaly values were not computed north of 54°.

Figure 5 contains a summary of the signs of the local anomalies for all 12 months. Where the local deviation is positive (temperature in the 2° square higher than the latitude average) in every one of the 12 monthly charts, the area is distinctively shaded and marked "plus". Likewise, the regions having constant negative anomaly are indicated, and between lie the bands where the margin between positive and negative anomalies fluctuated and the sign changed from one part of the year to another.

This chart therefore presents a modified form of annual temperature anomaly (compare Schott on Geographie des Atlantischen Ozeans, Tafel XII) which, interpreted in accordance with the suggestion just advanced regarding the general correspondence between anomalies and the direction of latitudinal transfer of surface-waters, fits in a satisfactory way the established general outlines of Atlantic surface-drift.

The large area of constant negative departure that extends from the Spanish Peninsula southwestward beyond the Cape Verde Islands is explainable as a result of the dominant set of ocean-currents southward at all seasons in this area. The northerly origin of the waters that spread southward near the American coast is similarly revealed by constant negative departures in the region from Newfoundland to Delaware Bay.

The great middle region is indicated by the character of the temperature-anomaly alone, as dominated by continual arrival of waters warmer than the latitude average (or generally of more southern origin). This is an area of well-charted surface-movements where warm waters move on a broad scale northward, through the Caribbean and Florida currents and the western half of the Sargasso Eddy, on into the great Atlantic Drift towards northern Europe. The borders of the area of constant positive deviation might well be taken as a chart of the general outline of the field of prevailing northward-setting currents.

Within the characteristic areas, however, the highly generalized representation of Figure 5 affords no means of distinguishing between strong well-marked currents like the Gulf Stream and the weaker and not so well-defined drifts such as that northward past Bermuda.

The twelve individual monthly charts for the region below 54° north containing average anomaly-values for each 2° square, which underlie the generalization of Figure 5, are available in manuscript form in Weather Bureau files, but space limits preclude publication here. Extreme local departures range from a value of +10° for the largest positive departure, which occurs in January at mid-ocean near 44° north and 30° west, to the largest negative deviations of -15° to -18°, which occur from December to June in the waters surrounding Newfoundland.

FIGURE 6

AVERAGE FREQUENCY OF LARGER ANOMALIES—ANNUAL BASIS

[Explanation--Frequency-distribution of larger monthly departures from latitude normal temperatures (shown in Fig. 2) based upon 63-year means by 2° squares. Warmer waters (anomaly +4° or more) indicated by cross-hatched shading; colder waters (anomaly -8° or more) shaded vertically. Indices, 4, 8, 12, etc., to be interpreted as showing occurrence of these larger departures in "four months of the year," "eight months of the year," "all months of the year," etc., in the average for the locality.]

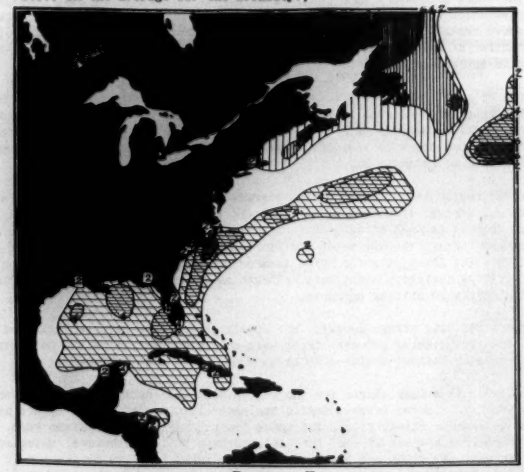

FIGURE 7

AVERAGE FREQUENCY OF LARGER ANOMALIES—JUNE TO NOVEMBER

[Explanation--See legend for Figure 6, but interpret indices, 2, 4, 6, as "two months in six," "four months in six," etc.]

This disparity of extreme values ("minus" much larger than "plus" values) illustrates a point which may be stated as follows: Intensified local cooling of a portion of the ocean-surface occurs more readily than local warming. This is well exemplified by the situation along the African coast at relatively warm latitudes down to the 15th parallel, where the negative anomaly reaches a value (-12°) larger than the positive anomaly anywhere. From 8° to 12° of deficiency is found during a large part of the year near (north of) Cape Verde.

By selecting representative limiting values for each type of anomaly a survey of the whole set of monthly charts can be made to bring into view the fields or areas of more exceptional departure which correspond to the stronger surface movements. Selection of positive values reaching or exceeding 4° F and of negative values -8° or more, is found to delimit the more important temperature-areas in sufficiently sharp detail.

The material of the monthly charts of average anomalies, when thus surveyed for frequency of occurrence of these limiting values, provides local frequency indices by 2° squares, which may be plotted to produce a summation-chart of the form shown in Figure 6. The scope of this and following figures is limited to the area between the 40th meridian and the American coast, inasmuch as the most pronounced contrast in currents occurs in that region, which is therefore best suited to show what advantage this method of survey has in it for evaluation of latitudinal transfer of temperature-effects through surface-drift.

The precise nature of the gradations of value on Figure 6 will be understood from the above description to represent frequency-indices, and not as a graduated scale of average temperature-anomalies. For example, the index "12" means that the average anomaly at that spot was up to or in excess of the limiting value (+4° or -8° F) in every one of the 12 months of the year; "6" indicates occurrence on the average in 6 months out of the year; etc.

It will be seen, in Figure 6, that only a few limited areas show prevalence of large-order anomalies in all months of the year, and that the regions are quite sharply defined which show an average of 6 or more months out of the year.

The influence of the Gulf Stream is made particularly graphic by this device and there comes to view a very interesting characteristic, which so far as can be ascertained has heretofore been overlooked, in that the elongated field of "plus" anomaly equivalent to the average drift of the Gulf Stream is, in this 63-year condensation of the Stream's temperature-history, broken into three well-separated nodes.

The first of these nodes lies below Hatteras, with a peak index of "12"; in other words, the anomaly is constantly above 4° in that sharply limited area. That this spot of constant high anomaly below Hatteras does not extend entirely to the Straits of Florida is in part at least a result of smoothing by the relatively large unit-area (a 2° rectangle) upon which the computations are based. The Stream is too narrow in the southern part to retain clear-cut identity with such a broad unit, and it is only towards Hatteras, where the current spreads to a width having better proportion to the space-unit, that this measure of anomaly truly represents the constancy of the thermal effect.

The two remaining nodes of relatively high constancy in the Gulf Stream (peak frequency 10 out of 12 months of the year) appear just eastward of the 70th and 60th meridians, respectively, the second spreading more extensively than the first.

At the two internodes, about due south of Cape Cod and Cape Sable, the high positive anomaly is much less constant and the limiting value occurs in less than half the months of the year.

It seems, upon this evidence, an inescapable conclusion that the Gulf Stream contains inherent dynamic forces which tend to break it into spatial movements of an eddylike nature that repeat themselves most commonly in certain geographical locations.

The great break at the tail of the Grand Bank, under the drive of the impinging Labrador Current, is very clearly illustrated in this method of charting. The spread and high constancy of the warm drift beyond that break, in the large area cut by the 40th meridian, are also clearly emphasized here.

No such nodal conformations as those along the course of the Gulf Stream are to be found in the region of negative anomaly that lies along the northern coast. Selection of a limiting value of -8° for that region would be expected to intensify any local contrasts which might exist, so that the absence of feature in that broad field of colder waters must be regarded as an evidence

FIGURE 8
TEMPERATURE DEPARTURES EXPERIENCED IN JANUARY 1932

[Explanation--Mean temperatures for a single month (January 1932), computed by 1° squares and expressed as departure from the 63-year average for the whole latitude-strip across the full breadth of the ocean. Heavy shaded band with maximum departures over +10° F shows localized influence of the Gulf Stream. Coldest areas--from Nova Scotia northeastward beyond Newfoundland--show temperatures more than 16° below the latitude average.]

of constancy in underlying causes which is in great contrast to the situation along the Gulf Stream.

To reveal the extent to which seasonal influence enters into the situation for the year as depicted in Figure 6, the component material obtained from the warmer half of the year (June to November), when the influence of cold continental air is least effective, is shown as Figure 7. The base for this chart being but six months, frequency-indices of "6", "3", etc., must be interpreted as "6 out of 6", "3 out of 6", etc. The three nodal spots persist on this chart, and, while the area of large negative anomaly is considerably reduced, the abnormal warmth of the Gulf of Mexico comes into greater prominence.

Up to this point the basic material has been exclusively obtained from the monthly normals by 2° squares, as published in the British "Marine Observer" for 1926. The long term of 63 years that underlies those averages must establish a high degree of credibility for the normal types of variation presented.

An important question remains, however, as to how far short-term, or contemporary, conditions fit or depart from the long-term average situation. To offer any information on that subject demanded that a large body of sea-temperature observations for limited time-units be computed in terms of the latitude temperature-normals.

The rich data available in the files of the Marine Division of the Weather Bureau for 1932 and 1933 have been treated to provide a sequence of 24 individual monthly charts, scaled to the more refined space-units of 1° squares.

A typical winter chart, for January 1932, is presented as Figure 8. This Figure might be called a synoptic chart of surface-drift in terms of temperature-anomaly. Because of the wealth

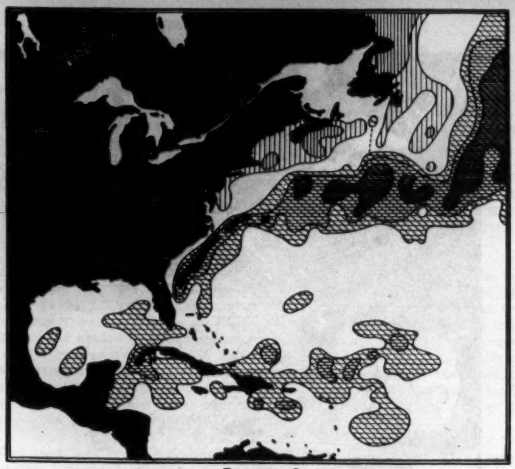

FIGURE 9
DISTRIBUTION OF LARGER ANOMALIES—AUTUMN OF 1932
[Explanation--Frequency-distribution of monthly temperature-anomalies actually experienced in September, October, and November of 1932 (Fig. 9) and 1933 (Fig. 10). Basis of shading, the occurrence of individual monthly anomalies in 1° squares compared to latitude normal, of +4° or more (cross-hatched areas) and -8° or more (vertical shadings). Light shadings indicate occurrence in one month of the three; medium shadings, two months in three; and heavy shadings, occurrence of these larger anomalies in all three months covered by the survey.]

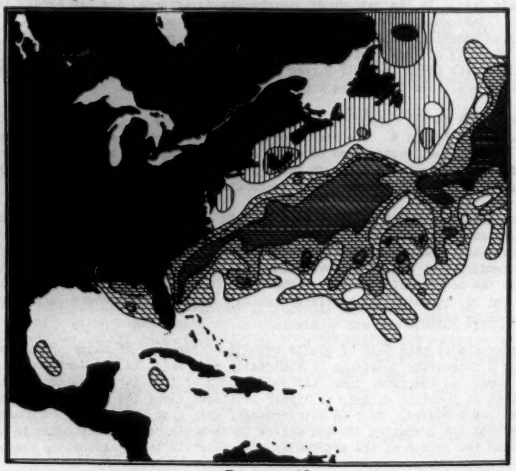

FIGURE 10
DISTRIBUTION OF LARGER ANOMALIES—AUTUMN OF 1933
[Explanation--See Figure 9.]

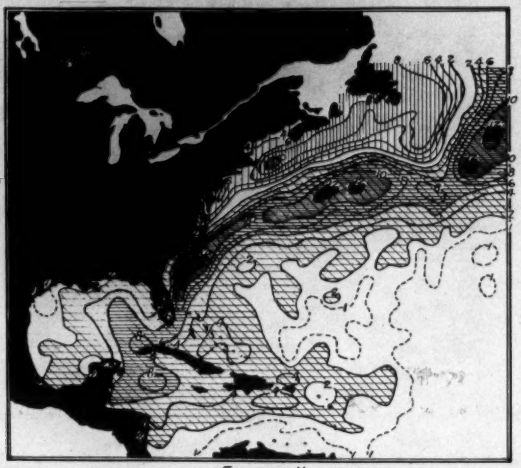

FIGURE 11
TWO-YEAR SUMMARY OF LARGER ANOMALIES, FOR 1932-33
[Explanation--Frequency-distribution of larger monthly anomalies (+4° and -8°) for two years, 1932-33, reduced to annual indices comparable with those of Figure 6. Warm areas are cross-hatched; cold are shaded vertically. Indices, 2, 6, 12, etc., are to be interpreted as "two out of twelve months," "six out of twelve," etc.]

of intricate detail in the pattern of temperature-departures, one can hardly escape, in looking at such an illustration, the view that here is a representation of complex fluid patterns in which eddying masses are reacting upon each other at a rate which has probably modified but not destroyed identity of individual bodies within the month which is the basis of this cross-section. The general effect along the Gulf Stream resembles a procession of masses rather than a steady-going current analogous to streams bound within fixed channels.

Space limits forbid reproduction here of the sequence of 24 months covered by our file of charts similar to Figure 8. One result of careful examination of the series can, however, be reported, namely, that there seems to be no definable sequence in the changing detail of area-patterns from month to month although large and irregular variations occur in respect to the size and shape of major features of the temperature picture.

In comparing months of the same name in 1932 and 1933 to determine how much of variation may be expected from one year to another the highest degree of contrast was found in the autumn season. The three-month periods comprising September, October, and November of 1932 and 1933 have been condensed to charts by development of frequency-indices for the limiting values (+4° and -8°) in the network of 1° squares comprising the field of study. The results are shown as Figures 9 and 10, in which the heaviest shading indicates areas where large anomaly was present during the whole season.

A comparison of this pair of charts reveals differences of major proportions. The autumn of 1932 had a noteworthy incidence of abnormally warm water in the West Indian Region which was absent in 1933. On the other hand, the fall season of 1933 far overshadowed the previous autumn in the extent of positive anomaly at higher latitudes along the Gulf Stream and thence southward into the Sargasso Region. Over an extraordinary area from Florida to the Grand Banks abnormally warm surface-waters prevailed for the entire three-month period, September to November 1933; at the same time the extent of the abnormally cool water in the Newfoundland region was greater than in 1932.

Similar comparisons of other seasons in these two years failed to show an equal degree of contrast in distribution of the significant fields of temperature-anomaly. A possible cause of the autumnal divergence may perhaps be found in the fact that several severe tropical disturbances passed northward along the American coast in the late summer and autumn of 1933. These storms had no counterpart in 1932 and in fact constituted a most unusual if not unprecedented series of tropical storm-movements.

The comparison just presented in Figures 9 and 10 indicates the extreme degree to which sea-temperatures in the western Atlantic vary in course of time. Additional evidence on this point is carried by Figure 11, the result of the final experiment in this study, wherein the 24 monthly charts for 1932-1933 were reduced to frequency-indices comparable to the 63-year average of Figure 6.

This two-year period fails in important details to reproduce the pattern of the long-term chart of temperature-anomalies. The nodal character of the Gulf Stream was somewhat less prominent in 1932-33, and the two outlying nodes, beyond Hatteras, were merged except at two closely adjacent spots of maximum frequency, where the temperature-departure was constantly above 4° (index "12") throughout the entire two-year period. Figure 6 shows that peak-frequency in this outer part of the Gulf Stream averages only 10 months out of 12, but in Figure 11 the area with an index "10" is much more extensive than the average and fully encompasses the locations of both nodal peaks beyond Hatteras on the long-term chart. More extensive and persistent warmth likewise prevailed in these two recent years over the Florida Current and its origins in the northwestern Caribbean Sea and southeastern Gulf of Mexico.

In still another important respect the warm drift in 1932-33 showed a radical extension as compared with the normal situation in Figure 6. Southwards of the Grand Bank the water was 4° or more above latitude normal during 50 to 70 per cent of the time (12 to 17 months out of 24) thus producing annual indices of "6" to more than "8", whereas the 63-year chart shows less than "2" as the average index in that place. At the same time the prevalence of cold drift over the Grand Bank was below average, the indices being reduced from an average of "10" to a value of "8" in 1932-33, east and southeast of Newfoundland.

In short, the situation for the two-year period, 1932-33, which is the basis of Figure 11, was definitely characterized by warmth more persistent and extensive than the average along the whole course of the Gulf Stream.

The causes and meaning of these demonstrated departures from the normal are entirely unexplored and constitute problems that invite further study in the hope of finding significant relations between atmospheric events and extensive variations in ocean-surface temperature. The basis for such work must be laid, however, in greatly lengthening the month to month sequence of contemporaneous temperature-surveys.

Acknowledgment--The assistance of David J. Stevlingson and Giles Slocum of the Marine Division, who by painstaking assembly of material and preparation of charts greatly aided this investigation, is hereby acknowledged.

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THE NATURAL REGIONS OF THE WORLD OCEAN ACCORDING TO SCHOTT

W. L. G. Joerg

One of the main objectives of modern geography is regional synthesis, that is, the creation of a composite picture of a given region based on an analysis of the constituent elements that give it its character and set it off from other regions. In discussing the geography of the lands it has hence long been customary to divide the area under consideration into regions of relatively homogeneous natural conditions. Whether the regions have been loosely or sharply defined, whether the approach to delimitation has proceeded from the central core outwards or has concentrated on the outer boundaries themselves, regional subdivision, both for the larger truth that generalization reveals and for economy in presentation, has been the organizing principle in the modern treatment of the geography of the lands [1]. (Numbers in brackets refer to "References and notes" at end of paper.)

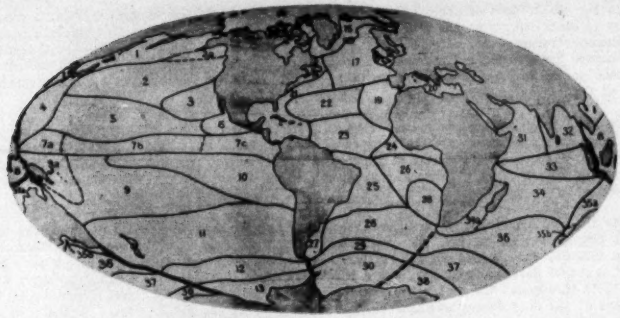

FIG. 1—THE NATURAL REGIONS OF THE WORLD OCEAN ACCORDING TO SCHOTT
(ON AITOFF'S OR HAMMER'S EQUAL-AREA PROJECTION)

[IN THE TEXT THE REGIONS ARE IDENTIFIED BY THEIR NUMBERS AND DESCRIBED; TO THIS WORLD MAP HAVE BEEN TRANSFERRED THE REGIONAL OUTLINES FROM SCHOTT'S FORTHCOMING MAP OF THE NATURAL REGIONS OF THE INDIAN AND PACIFIC OCEANS AND FROM AN UNPUBLISHED MAP BY HIM OF THE NATURAL REGIONS OF THE ATLANTIC; CREDIT FOR THE WORLD MAP SHOULD REST EXCLUSIVELY WITH SCHOTT]

Regional oceanography

The same method may be applied with equal cogency to the sea. The seaman has of course long recognized the diversity of the ocean vastnesses that he crosses, as regards their prevailing winds and currents and other phenomena, and has characterized some of these areas by such terms as "roaring forties," doldrums, Sargasso Sea, and Gulf Stream. But it has taken the development of a science of oceanography, and especially of physical and dynamic oceanography as contrasted with the earlier dominant biological oceanography, to create conditions favorable to the application of the concept of regional synthesis to the sea. Such monographs on individual areas as Helland-Hansen and Nansen's "Norwegian Sea" [2] and Bigelow's "Gulf of Maine" [3] are evidences of the new orientation.

The first to apply the concept to a whole ocean, however, and the first to work out a subdivision into natural regions was Gerhard Schott of the German Hydrographic Office in Hamburg in his "Geographie des Atlantischen Ozeans," which was published in 1912. To be sure, prior to this, a number of world classifications of climate had appeared in which the climatic provinces were extended over the oceans [4] but as, naturally, they dealt only with conditions in the air above the surface of the water, they did not take into account the properties and movement of the water itself, and it is these that primarily come into consideration in an oceanographical subdivision. In his book on the Atlantic (the treatment of these matters is unchanged in the second, revised edition of 1926) Schott presents two regional subdivisions of that Ocean, one based on hydrology, mainly temperature, salinity, and horizontal and vertical circulation (1926 edition, p. 155), and the other based on climate, mainly atmospheric temperature, pressure, winds, and precipitation (p. 234). In a forthcoming book on the geography of the Indian and Pacific oceans [5], which thus completes his survey of the oceans of the world, Schott combines hydrology and climate and presents a single map of the natural regions of both oceans.

On the accompanying map (Fig. 1) these delineations have been united into one picture to show the natural regions of the world ocean. This has been made possible through the kindness of Dr. Schott in sending for the present meeting a proof of his regional map of the Indian and Pacific oceans and an original manuscript map by himself of the natural regions of the Atlantic which integrates the two maps in his book on that Ocean and is hence comparable to the forthcoming map of the Indian and Pacific oceans [6]. As a result, thus, of his digest of the enormous relevant literature, quickened by personal experience of the Seven Seas, there is here available for the first time a regional survey of the oceanic waters of the globe [7].

The zonal arrangement of the regions

Although disturbed by the irregularity of the distribution of land and water on the globe, the pattern of natural regions discloses, broadly, an arrangement in latitudinal belts which reflect the great climatic zones. Our rapid survey of the regions [8] had hence best follow these

belts. Of these there are five--two polar, two mid-latitudinal, and one tropical. Each ocean encompasses the whole series from north to south, except the Indian Ocean, which, because of the Asiatic landmass, lacks the northern polar and the northern mid-latitude belts.

The two polar belts

The two polar belts each consist of two sub-belts. In the north both are developed only in the Atlantic gore, namely, as the Arctic Region (14 on Fig. 1), embracing the Arctic Sea (which is an appendage of the Atlantic Ocean), Baffin and Hudson bays, and the cold waters along the East Greenland Coast, and as the Atlantic Sub-Arctic Region (15), which extends from Labrador to Novaya Zemlya. In the Pacific only the sub-Arctic is represented, namely, by the northern part of the East Asiatic Marginal Seas (1), essentially Bering and Okhotsk seas.

In the south the absence of interfering landmasses permits the uninterrupted development of both polar sub-belts, namely, the Antarctic Region (13, 30, 38) and the Sub-Antarctic Region (12, 29, 37). The boundaries between adjoining pairs of the three oceans, namely, the axis of the submarine ridge from Tasmania via Macquarie Island to Cape Adare [9], South Victoria Land, and the conventional meridians of Cape Horn and the Cape of Good Hope, do not break the continuity of these two circumterrestrial belts. The northern boundary of the Sub-Antarctic Region, which passes through Macquarie and Kerguelen and between South Georgia and the Falklands, is the Antarctic Convergence, or contact-line where the cold heavy Antarctic water meets the warmer lighter water of the southern mid-latitude belt and sinks northward below it [10].

The two mid-latitude belts

Of the two mid-latitude belts the southern is again the more continuous because of lesser interruption by land. The northern mid-latitude belt consists, in the Pacific, of the middle section of the East Asiatic Marginal Seas (1), embracing probably the Sea of Japan, the Yellow Sea, and the East China Sea, of the North Pacific Mid-Latitudes (2) including the Alaska Subregion (2a), and of the California Region (3); and, in the Atlantic, of the Northwest Atlantic Marginal Seas (16), the northern part of the Gulf Stream Region (21), the Northeast Atlantic Drift Region (17), the North and Baltic seas (18), the Morocco Region (19), and the Mediterranean Sea (20).

The southern mid-latitude belt consists of the South Pacific Mid-Latitudes (11) and, in the Atlantic, of the Patagonian Region (27), the South Atlantic Mid-Latitudes (26), and the Southwest African Region (28) as well as, in the Indian Ocean, of the South Indian Mid-Latitudes (36) and, probably, the Southwest Australian Region (35b).

The mid-latitude regions (2, 21, 17, 11, 26, 36) are primarily the areas of dominant westerly winds and easterly currents, somewhat less prominently developed in the Pacific in summer (August in North Pacific, February in South Pacific). In the Atlantic the easterly and northeasterly currents (of 21 and 17) carry temperate conditions farther poleward than anywhere else on the globe. The boundary between the Northeast Atlantic Marginal Seas and the Gulf Stream is an abrupt transition from colder to warmer waters now recognized as the Arctic Convergence--the northern counterpart of the Antarctic Convergence--and long known as the "cold wall," apparent even to the tourist voyaging between New York and Bermuda [11]. The cold segments (representing deeper waters coming to the surface) of the basic circulatory current-systems on both sides of the equator in each ocean (on one side only in the Indian Ocean), clockwise in the northern hemisphere, counter-clockwise in the southern, which impinge on the western sides of the continents, account for the California Region in the Pacific, for the Morocco Region and its counterpart, the Southwest African Region, in the Atlantic, and, in the Indian Ocean, the Southwest Australian Region. These cold-current segments are reinforced by the cold upwelling waters which represent compensations on these coasts of the water displaced by offshore winds. That no corresponding region has been set off by Schott on the west coast of South America, where the cold waters of the Peruvian Current [12] create analogous conditions, may be due to the fact that the larger forces dominating the whole sweep of the South Pacific may be considered as more important subdivisional criteria than the relatively local factors of coastal current and upwelling. In any case, the Galapagos Region (10), here interpreted as belonging to the tropical belt, contains the great westward sweep of cooler waters extending along the mathematical equator, which lies considerably south of the thermal equator. The Patagonian Region, finally--to complete this brief characterization of the natural regions of the two mid-latitude belts--is a shelf sea of relatively warmer water (from insolation?), flanked on its margin by the cold northward-flowing Falkland Current. It has certain similarities to the Northwest Atlantic Marginal Seas.

The tropical belt

The tropical belt consists of the following in the Pacific: The southern section of the East Asiatic Marginal Seas (1), that is, the northern part of the South China Sea, then the Malayan Seas (8), the Japanese Region (4), the North Pacific Trade-Wind Region (5), the Mexican Region (6), the Pacific Equatorial Region (7), in longitude divided into three parts (7a, 7b, 7c) the South Pacific Island-Dotted Region (9) with its Monsoonlike Subregion (9a), and finally the Galapagos Region (10).

In the Atlantic the tropical belt includes the southern part of the Gulf Stream Region (21), that is, mainly the Gulf of Mexico and the Caribbean, the Sargasso Sea (22), the North Atlantic Trade-Wind Region (23), the Atlantic Equatorial Region (24), the Brazilian Region (25), and the Ascension Region (26).

In the Indian Ocean the tropical belt consists of the Arabian Sea Region (31), which includes the Red Sea and the Persian Gulf, then the Bay of Bengal Region (32), the Indian Equatorial Region (33), the Mauritius Region (34), with the Mozambique Subregion (34a), and lastly the Northwest Australian Region (35a).

The boundary between the Indian and Pacific oceans in the tropics extends from Singapore along the east- and north-facing coasts of Sumatra and Java, then via Sumba, Timor, Timor Laut, and Arru to the southwest-facing coast of New Guinea, which it follows until it crosses Torres Strait to end in Cape York. The Arafura Sea and the Gulf of Carpentaria hence belong to the Indian Ocean, whereas the Sunda, Flores, and Banda seas are assigned to the Pacific "because decided East Asiatic influences make themselves felt in the surface-waters as far as Singapore and recent deep-sea investigation has confirmed the long-held assumption that the circulation in the numerous small but deep sea-basins of the Malay Archipelago derive their régime from the Pacific Ocean" [13].

Just as the two mid-latitude belts are preeminently the areas of westerly winds and easterly currents, so the tropical belt is primarily the zone of the trade-winds and westerly currents. The northeast trades and the southeast trades, blowing in oblique convergence on the equator, give propulsion respectively to the southwest- and west-flowing segments of the circulatory current-systems on both sides of the equator in each ocean (on one side only in the Indian Ocean). These paired belts are, in the Pacific, regions 5 and 9-10 enclosing region 7, in the Atlantic regions 21 (southern part) to 23 and 25-26 enclosing 24, and in the Indian Ocean region 34-35a flanking region 33. Regions 7, 24, and 33 are the equatorial belts, each characterized in general by westward-flowing parallel North and South Equatorial Currents (the North Equatorial Current in the Indian Ocean is reversed during the southwest monsoon) enclosing a narrow eastward-flowing Equatorial Countercurrent.

The remaining regions of the tropical belt, and some of those already mentioned, may be characterized as follows. In the Pacific the unity of the Malayan Seas, which include the basins of the Malay Archipelago and the southern two-thirds of the South China Sea, has already been dwelt upon. The Japanese Region is a proximate counterpart of the Gulf Stream Region and contains the curving transformation of the North Equatorial Current into the Kuroshiwo; on its eastern side it is structurally defined by the Bonin-Guam-Yap-Pelew Ridge. The Mexican Region is the area of extremely high temperature of the surface-waters (over 28° C for most of the year) straddling the eastern end of the Indian-Pacific thermal equator. The Monsoonlike Subregion derives its name from the seasonal reversal of the winds from southeast in August to north and northwest in February. The special characteristics of the Galapagos Region have already been mentioned.

In the North Atlantic the "eye" of the circulatory current-system, with no well-defined currents of its own and with its quantities of floating gulfweed, is known to all as the Sargasso Sea. The Atlantic Equatorial Region is the area of the Guinea (counter) Current and the southwest monsoon, sharply differentiating it from the adjoining trade-wind belts. The belt of the southeast trades is divided into an eastern part, the Ascension Region (named after Ascension Island), characterized by the cooler waters of the west-northwest and west-flowing Benguela Current, and a western part, the Brazilian Region, in which the same current, here in its southwest-flowing segment known as the Brazil Current, carries its warmer waters relatively far south on the South American coast.

In the Indian Ocean the Arabian Sea and Bay of Bengal Regions are the monsoon areas par excellence. In the winter under the northeast monsoon southwest-flowing currents develop on the eastern sides of these embayments, producing a decided clockwise circulatory system in the Bay of

Bengal and a tendency to such a system in the Arabian Sea. Under the summer southwest monsoon currents emanating from the Gulf of Aden and the Somali Coast strive northeastward, are deflected southeastward by the peninsula of India, and resume their northeastward course again in the Bay of Bengal. Under this régime the current along the Malabar Coast maintains the same direction, south-southeast, throughout the year. The area between the Laccadive-Maladive axis and this coast is hence not included in the Arabian Sea Region but assigned to the Bay of Bengal Region. In passing it may be remarked that the Red Sea and the Persian Gulf, dead-end arms (the Suez Canal does not count hydrologically) of the Arabian Sea, have the warmest oceanic surface-waters on the globe, reaching August means respectively of 31°5 and 32°3 C. The Indian Equatorial Region includes, besides its counter-current, the westward-flowing North Equatorial Current of the northern-hemisphere winter, whose direction, as already indicated, is reversed in the summer and becomes the Monsoon Current, which makes itself felt south to about latitude 5° south. The Mauritius Region is the belt of southeast trades and west-flowing South Equatorial Current, from which the area between Madagascar and Africa, where this current is forced around both ends of Madagascar and flows south to form the warm Agulhas Current which just reaches around the Cape of Good Hope, is set apart as the Mozambique Subregion. The Northwest Australian Region is the area traversed by the current that diverges from the northwest-flowing South Equatorial Current in the southern summer and flows north and northeast off the western coast of Australia.

Conclusion

This completes the survey of the natural regions of the world ocean. In this survey it has necessarily been possible to present only the barest outline. The substantiating details and the characterization of the different regions are set forth in masterly fashion in the already published and in the forthcoming volume. Through the completion of his trilogy Schott, it may not unfairly be said, has done for regional oceanography what Suess and Hann in their classic works did, respectively, for the regional geology and climatology of the world.

References and notes

[1] A. J. Herbertson, The major natural regions: An essay in systematic geography, Geog. J., v. 25, pp. 300-312, 1905; idem, The higher units, Scientia, v. 14, pp. 199-212, 1913; W. L. G. Joerg, The subdivision of North America into natural regions: A preliminary inquiry, Ann. Ass. Amer. Geog., v. 4, pp. 55-83, 1914; J. F. Unstead, A synthetic method of determining geographical regions, Geog. J., v. 48, pp. 230-249, 1916; R. M. Roxby, The theory of natural regions, Geog. Teacher, v. 13, pp. 376-382, 1925-26; S. Passarge, Vergleichende Landschaftskunde, 4 parts, Berlin, 1921-24; idem, Die Landschaftsgürtel der Erde, Breslau, 1st ed., 1923, 2nd ed., 1929; E. Markus, Naturkomplexe, SitzBer. Natf. Ges., Univ. Dorpat, v. 32, pp. 79-94, 1925.

[2] B. Helland-Hansen and F. Nansen, The Norwegian Sea: Its physical oceanography based upon the Norwegian researches 1900-1904, Report on Norwegian Fishery and Marine Investigations, v. 2, pt. 1, pp. 1-390, 1909.

[3] H. B. Bigelow, Physical oceanography of the Gulf of Maine, Bull. Bur. Fisheries, v. 40, pt. 2, pp. 511-1027, Washington, 1924.

[4] R. Hult, Jordens Klimatområden: Försök till en indelning af jordytan efter klimatiska grunder, Vetensk. Medd. Geogr. Fören. Finl., v. 1, pp. 140-201, with world map, Helsingfors, 1892-93; W. Köppen, Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt, Geog. Zs., v. 6, pp. 593-611 and 657-679, with world map, 1900. Köppen later refined his subdivision in: Klassifikation der Klimate nach Temperatur, Niederschlag und Jahreslauf, Petermanns geogr. Mitt., v. 64, pp. 193-203 and 243-248, with world map, 1918, and "Die Klimate der Erde: Grundriss der Klimakunde," with same map, Berlin and Leipzig, 1923. (The map has also been published separately as a wall-map on Mercator's projection, in slightly modified form, by W. Köppen and R. Geiger, Gotha, 1928.)

Of certain constituent elements of climate, especially precipitation, world maps had also been previously published in which the classification used was extended over the oceans, for example, the maps of rainfall-regions according to seasonal distribution by Köppen (Berghaus' Physikalischer Atlas, pt. 3, Pl. 12, Gotha, 1887; reprinted in Atlas of Meteorology by J. G. Bartholomew and A. J. Herbertson, Pl. 19, Edinburgh, 1899), by A. Woeikof (Die Klimate der Erde, Pl. 17, 2 vols., Jena, 1887) and in the atlases of the three oceans prepared by the Deutsche Seewarte, Hamburg (Atlantic, 1882, Pl. 29, 2nd ed., 1902, Pl. 29C; Indian, 1891, Pl. 27; Pacific, 1896, Pl. 25). In two of these atlases there are also maps of the wind-regions (Indian, Pl. 22; Pacific, Pl. 20).

[5] Geographie des Indischen und Stillen Ozeans, C. Boysen, publisher, Hamburg. (Since this paper was read the work has appeared as a volume of xx + 413 pages and 37 plates.)

[6] The proof map of the Indian and Pacific was centered on the meridian of 150° east, the manuscript map of the Atlantic on 30° west. Transference to a world map involved the selection of a projection with still another central meridian in order to avoid as much as possible disrupting the continuity of any one of the three oceans. Aitoff's (or Hammer's) equal-area projection centered on 60° west was the projection chosen (Fig. 1). This is the same projection, with the same central meridian, used by Schott for his bathymetric map of the world ocean (in Alexander Supan, Grundzüge der physischen Erdkunde, 7th ed., edited by Erich Obst, v. 1, Pl. 4, Berlin and Leipzig, 1927) and his world map of ocean-currents (Schott, Physische Meereskunde, p. 126, Berlin and Leipzig, 1924). Use of 160° west as the central meridian also maintains well the continuity of all three oceans, as the east and west borders then come to fall on 20° east--the meridian of the Cape of Good Hope, which is the accepted conventional boundary between the Atlantic and Indian oceans. An example of this centering, on the similar Mollweide's projection, will be found in the world map of ocean-currents in A. Allix and A. Leyritz, Géographie générale, p. 78, Paris, 1934.

[7] An earlier subdivision, by E. Markus (Meerestypen, Met. Zs., v. 47, pp. 402-411, with map Fig. 5, 1930; noticed by H. A. Marmer, Geog. Rev., v. 21, p. 678, 1931), is somewhat schematic and takes into account as subdivisional criteria only water-temperature and rainfall. The subdivision by the International Hydrographic Bureau (Limits of oceans and seas, Spec. Pub. No. 23, with map, Monte Carlo, 1928) is primarily dictated by expediency, its purpose being to establish a classification to be followed in the arrangement and division of the various volumes of Sailing Directions.

[8] Based mainly on "Geographie des Atlantischen Ozeans," edition of 1926, and the materials kindly placed at the writer's disposal by Dr. Schott, which were, in view of the stage of the forthcoming volume on the Indian and Pacific oceans, necessarily limited to the following proofs in addition to the two maps mentioned above: Table of contents of the whole volume, brief general introduction to the section on the natural regions of the Indian Ocean, detailed discussion of the Arabian Sea, and four maps of the Indian-Pacific showing surface-water temperatures in August, atmospheric pressure and winds in August, currents in the northern-hemisphere summer, and the same in winter. For the resulting deductions and substantiations that follow in the text the writer alone is responsible.

[9] Bathymetric Map of the Antarctic (Southern Atlantic, Indian, and Pacific oceans), 1:20,000,000. Accompanies W. L. G. Joerg, Brief history of polar exploration since the introduction of flying, Amer. Geog. Soc., Spec. Pub. No. 11, 2nd revised ed., New York, 1930. A revised edition of the map, reduced to 1:25,000,000, appeared as Pl. 1, Geog. Rev., v. 22, 1932.

[10] G. E. R. Deacon, A general account of the hydrology of the South Atlantic Ocean, Discovery Reports, v. 7, pp. 171-238, Cambridge, 1933, especially pp. 190-193 and Fig. 11 (on p. 192 the development of the concept by Meinardus, 1923, and by Wüst and Defant, 1928, is sketched); H. U. Sverdrup, ibid., pp. 148-150, 1933; D. Dilwyn John, The second Antarctic commission of the RRS Discovery, Geog. J., v. 83, pp. 381-398, 1934, especially pp. 383-384 and Map 2.

The Antarctic Convergence supplies a truly significant natural northern boundary for an Antarctic Ocean, if it is desired to distinguish such a unit. Because of the impingement on this contact line both of contrasted current-directions (northeast and southeast) and water-temperatures it is an important boundary for marine organisms and for ice. Because of the checked northward flow and sudden increase in temperature of the water, pack-ice does not proceed beyond it, and the Antarctic Convergence hence represents the extreme northern limit of its distribution (Deacon, op. cit., p. 193).

A Southern Ocean is segregated by Vallaux, which he conceives as extending northward to the boundary between the trade-wind belt and the belt of westerlies in about latitude 35° south (Camille Vallaux, Géographie générale des mers, pp. 43, 33-34, map p. 180, Paris, 1933; see also his l'Océan Austral, Ann. Géog., v. 35, pp. 481-498, 1926, and his La classification des océans et des mers, Géographie, v. 50, pp. 184-202, especially pp. 194-197, 1928).

However, the concept both of an Antarctic Ocean and a Southern Ocean, while understandable from a nautical point of view, does not take into account the physical unity of the great ocean-basins, as established by recent research, especially of their vertical circulation (Joerg, p. 86 of text cited above in Note 9). The findings both of dynamic oceanography and of structural geology point to the desirability of recognizing three major oceans, and three only, as Schott has here done.

The Antarctic Convergence is only one of several contact surfaces of contrasting waters that recent oceanographical analysis has disclosed. A northern counterpart, the Arctic Convergence, is mentioned further on in the text. Two further pairs are recognized, a northern and southern Subtropical Convergence and a northern and southern Tropical Convergence. These are shown on the summer and winter current-maps of the Indian-Pacific in Schott's forthcoming book. For their representation in the Atlantic, which is necessarily lacking in Schott's book on the Atlantic because its publication antedates these investiga-

tions, one should turn to Deacon's Fig. 11 and Dilwyn John's Map 2 referred to above. Wüst also shows them in the Atlantic (map facing p. 528 in G. O. Wüst, Der Ursprung der atlantischen Tiefenmässer, Sonderband der Zs. Ges. Erdk., Berlin, pp. 506-534, 1928; see caution, however, in Deacon, op. cit., p. 192).

[11] For a remarkable photograph, taken south of Newfoundland in 41° 40' north and 51° 07' west, see Edward H. Smith, The Marion expedition: Scientific results, pt. 3, p. 204, U. S. Coast Guard, Washington, 1931.

[12] For a description of the Peruvian Current embodying an analysis of the latest material and an examination of the causes of its widespread displacement, see Gerhard Schott, Der Peru-Strom und seine nördlichen Nachbargebiete in normaler und anormaler Ausbildung, Ann. Hydrogr., v. 59, pp. 161-169, 200-213, 240-253, with map, 1931 (abstracted by R. C. Murphy, Geog. Rev., v. 22, pp. 148-150, 1932). An earlier interpretation is Camille Vallaux, The question of the Humboldt Current, Hydrogr. Rev., v. 7, pp. 66-74, 1930.

[13] Translated from page-proof, "Geographie des Indischen und Stillen Ozeans," p. 185.

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EXPLORATION OF CALIFORNIA SUBMARINE CANYONS

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(Abstract)

The writer spent a sabbatical leave from the University of Illinois investigating the canyons which have been found in abundance along the slopes off the California Coast. Many of these canyons start almost at the shore-line and in some cases they are traceable outward to depths of over 11,000 feet. Below their rims they have depths comparable to the greatest land canyons and would certainly constitute some of the scenic wonders of the world if they were exposed to view. These submarine depressions have been a subject of controversy among California geologists and their origin as submerged river valleys has been challenged by several writers (W. M. Davis, Submarine mock-valleys, Trans. Amer. Geophys. Union, 13th Annual Meeting, pp. 231-234, 1933; A. C. Lawson, The continental shelf off California, Bull. Nation. Res. Council, No. 44, 3-23, 1924; W. S. T. Smith, Submarine valleys of the California Coast, Science, v. 15, pp. 670-672, 1902). The alternatives of submarine currents or diastrophic movements were considered by these geologists to be more in accord with the indications of coastal elevation which are found in California.

In order to determine which of these alternatives was the most reasonable explanation for the submarine canyons it was important to make accurate determination of the shapes of some of the canyons and to find as much as possible about the character of the rest. On land it is generally easy to distinguish the difference between diastrophic and river-cut valleys, particularly if the river-valleys are in the youthful stage where they still maintain their V-shaped cross-sections. Regarding submarine currents the suggestion has been made that the valleys were not actually cut by the currents, but represent elongate tracts kept free from deposition by outward moving currents while banks of sediment were accumulating on either side. Depressions of this sort should have relatively gentle slopes, basin-depressions along their courses, and walls made of fine sediments.

With these considerations in mind numerous observations were made. The heads of two of the canyons were surveyed with enormous detail so that very exact contour-maps and sections could be prepared. The soundings made recently by the Coast and Geodetic Survey over most of the territory were studied and contour-maps and sections were drawn as accurately as possible from these. In addition, hundreds of bottom-samples were collected from the floors and walls of the canyon.

The results of this work have been the finding that the submarine canyons are decidedly of the river-valley type, having close resemblance to the V-shaped canyons cut into the margins of plateaus. Wherever the surveys were detailed, the sinuous courses of the canyons and the typical river-patterns of tributaries could be determined and the practically continuous outward slope of the floor was evident. These are characteristics quite foreign to diastrophic valleys and are certainly not what would be expected of depressions maintained by submarine currents. Furthermore, all but one canyon where dragging for sediment was carried on was found to have rocky material on the sides which certainly eliminates the non-deposition hypothesis suggested by Davis and Lawson. The finding of finer sediments in the canyon-bottoms than on the adjacent shelves was suggestive of the feebleness of currents within the canyons.

The only reasonable conclusion from the information now available is that the canyons were cut by rivers. Questions which are not as easily decided are at what time the rivers were flowing out over what are now submarine slopes and also the nature of movements which lead first to the uncovering of the slopes and later to their submergence.

Time of canyon-cutting--Several considerations make it evident that the canyons were not cut at any very remote geological period. The instability of the California Coast makes it probable that if the canyons had been long submerged they would have been warped and faulted, losing their regular outward slopes which are so evident from the surveys. Also the rock dredged from their walls is of late Tertiary age in some cases which shows that the canyons cut through this rock are still younger. Finding river-valleys directly inside the canyons which are related in such a way to the later Tertiary or Pleistocene deformations as to imply a relatively recent origin adds further proof of the recency of the canyon-cutting. On the other hand, the canyons must have been submerged at least many thousands of years since there is a very evident lack of deep estuaries running into the land such as might be expected from a recent great submergence of land valleys. Clearly the coast has had time to become straightened. Also the marked change in character between most of the land valleys inside and the submarine canyons indicates that there have been extensive changes due to erosion or deposition affecting the landward side since submergence took place. The unchanged condition of the marine canyons during this process is thought to imply that deposition within the canyons has built up masses of mud which flowed outward after sufficient accumulations had occurred leaving the inner portions relatively free from filling.

Cause of the emergent sea-bottom--While it would not be particularly surprising if the California Coast had been subject to enormous up-and-down movements such as are implied by the submarine canyons, it becomes less comprehensible that practically all of the rest of the coastline of the world would have had to have had the same movements since submarine canyons are found along practically all coasts where the slopes have been well sounded. Still more perturbing to the idea of coastal elevation and submergence is the finding of similar canyons off such oceanic islands as the Hawaiian group. The only alternative which seems to be available is that the sea-level has been changed by some uncertain process.

[It is expected that the complete paper will be published later by the Geological Society of America.]

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HYDROGRAPHIC RELATIONS BETWEEN THE SO-CALLED GULF STREAM AND THE GULF OF MEXICO

A. E. Parr

The following is an abbreviated report on hydrographic observations in the Gulf of Mexico. A full account of the investigations will be published shortly as Bulletin of the Bingham Oceanographic Collection, Volume 5, Article 1.

Previous to 1932, only a few temperature-sections through the Gulf of Mexico were available, but there was no record of any general oceanographic survey, combining temperature-observations with determinations of the chemical properties of the water-masses. To supply this want, an oceanographic expedition to the Gulf of Mexico was sent out by Yale University during the winter of 1932, under the auspices of the Bingham Oceanographic Foundation, on the schooner Mabel Taylor, with the cooperation of its owner, Mr. Drayton Cochran.

The writer is also indebted to the Woods Hole Oceanographic Institution for permission to use for comparisons in the present report on the results of the Mabel Taylor Expedition some of the observations subsequently gathered by the Atlantis on Caribbean cruises sponsored jointly by the Woods Hole Oceanographic Institution and the Bingham Oceanographic Foundation of Yale University. A full account of the Atlantis observations will appear later as a separate publication.

Due to the previous lack of information, the nautical presentation of the course of the so-called Gulf Stream, indicating that it should make an enormous clockwise detour through almost the entire Gulf of Mexico, has become quite generally accepted as a picture of the actual paths of water-transportation through this region. Recently, however, strong objections to this viewpoint have been raised by the Danish oceanographer Nielsen [3], but actual observations from the

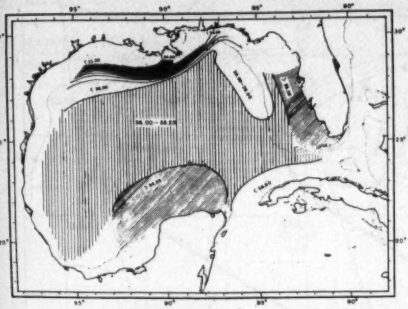

FIG. 1—AVERAGE SALINITIES IN UPPER 50 METERS, MABEL TAYLOR OBSERVATIONS

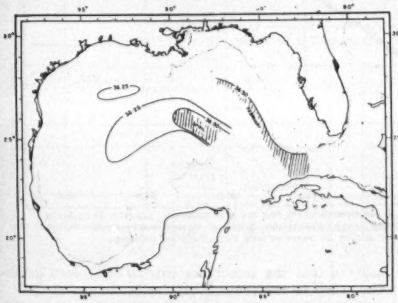

FIG. 2—CONTOURS OF INTRUSION OF CARIBBEAN WATER INTO GULF OF MEXICO BELOW ENDEMIC SURFACE-LAYER (MEDIAN DEPTH ABOUT 200 METERS), FEBRUARY AND APRIL, 1932, MABEL TAYLOR OBSERVATIONS

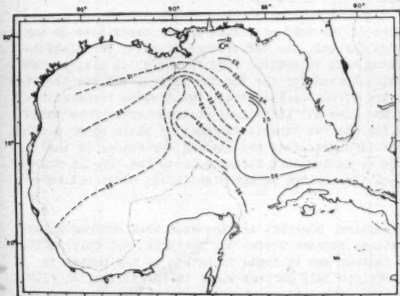

FIG. 3—DISTRIBUTION OF SURFACE-TEMPERATURES (°C), GULF OF MEXICO, FEBRUARY (——) AND APRIL (- - -) 1932, MABEL TAYLOR OBSERVATIONS

Gulf itself were still lacking and some of Nielsen's premises have therefore proved erroneous, although his conclusion that the so-called Gulf Stream on the whole simply takes the shortest possible path from the Yucatan Channel to the Straits of Florida is fully confirmed by the observations here reported upon.

Considering first the distribution of surface-salinity (average salinities in the upper 50 meters), the justification of Nielsen's contention is immediately obvious from our Figure 1, based upon the Mabel Taylor results. The low-salinity surface-layer characteristic of the entire Caribbean Area enters with the current through the Yucatan Channel and distributes itself in a narrow band directly to the Straits of Florida without deviating at all into the Gulf of Mexico where higher surface-salinities prevail. It may be pointed out, however, that this distribution of surface-salinities is a direct opposite of that assumed by Nielsen, who argued that if the surface-waters of the Gulf of Mexico contributed to any significant extent to the surface-waters of the Florida Current, they would make themselves felt as a freshening influence, on the assumption that the Gulf of Mexico would have generally lower (not higher) surface-salinities than those of the Caribbean Area.

At a depth of about 200 meters, however, the picture is totally different. At this level we find an intrusion of typical Caribbean water of the maximum salinity layer (salinities higher than 36.5 per mille) extending for a considerable distance into the Gulf, as shown in Figure 2. This intrusion underwent a very considerable change either in extent or in location or in both between February and April, 1932, as also indicated in our illustration. The layer is very thin, however, of only about 50-meter thickness, and probably largely dissipates itself by admixture into the water-masses of the Gulf of Mexico, representing the Caribbean contribution to the characteristic endemic mixture found in the Gulf. In any event, the intrusion can certainly not represent a significant deviation of the Yucatan to Florida Straits Current in terms of actual volume of transportation as compared with the tremendous volume transported by the rapid flow over the direct path.

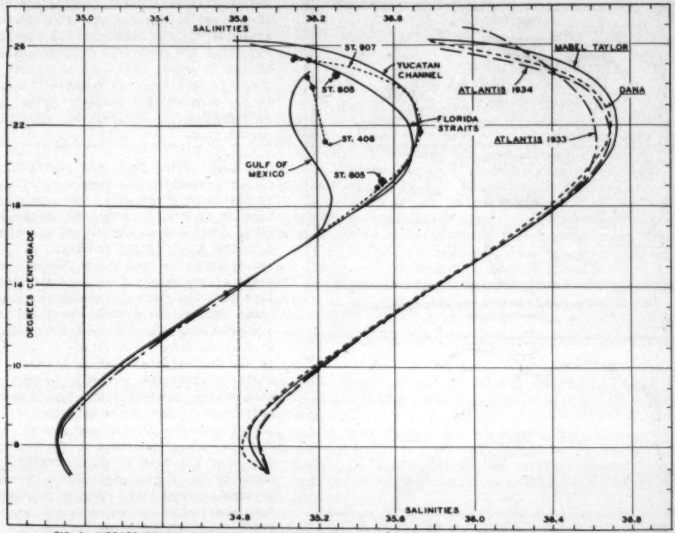

FIG. 4—AVERAGE TEMPERATURE-SALINITY CORRELATION-CURVES (LEFT) FOR YUCATAN CHANNEL, STRAITS OF FLORIDA, AND GULF OF MEXICO PROPER AS OBSERVED BY MABEL TAYLOR EXPEDITION; AVERAGE TEMPERATURE-SALINITY CORRELATION-CURVES (RIGHT) FOR ALL AVAILABLE SERIES OF OBSERVATIONS FROM YUCATAN CHANNEL

It is interesting to observe in this connection that the subsurface intrusion of warm Caribbean waters into the Gulf in the manner just described is the controlling factor in the distribution of winter temperatures in the endemic surface-waters of the Gulf, superjacent to but quite distinct from the intrusion itself, as shown by the exact manner in which the shift of the boundaries of the subsurface intrusion is reflected by the corresponding shift in the course of the surface-isotherm during the same period (compare Figs. 2 and 3).

For determining whether the endemic waters of the Gulf of Mexico proper contribute in any significant degree to the waters of the Florida Current, the temperature-salinity correlation-method of identifying oceanic water-masses seems most suitable. From Figure 4, it will be seen that, while the temperature-salinity correlation-curves for the Yucatan Channel and the Straits of Florida, as observed by the Mabel Taylor, are virtually identical, the average temperature-salinity curve for the Gulf of Mexico proper and also all individual station-curves from this region are totally different from the curves for the two straits at least in their upper portion (upper couple of hundred meters). Under these circumstances, the lack of any change in the temperature-salinity correlation-curve for the so-called Gulf Stream between the Yucatan Channel and the Straits of Florida is adequate proof of the absence of any significant contribution of Mexican Gulf waters to the Florida Current.

From the distribution of the surface-salinities, however, we have seen that surface-waters of Gulf type occurred at the northernmost stations between Havana and Tortugas, but only on the northern banks well inside of the 100-fathom contour was it found to extend to the bottom in 1932. In Figure 5, the distribution of this Mexican Gulf surface-water in the Straits of Florida, as observed by the Mabel Taylor, is compared with earlier observations by the Dana and later records obtained by the Atlantis. The Atlantis observations give essentially the same picture as that obtained from the Mabel Taylor investigation. In both cases we see a surface-sheet of pure Gulf type, not exceeding 100-meter thickness, superimposed upon pure Caribbean waters below. And in both instances, we find the Gulf water present in this western portion of the Straits of Florida confined to what in the West Indies Pilot, issued by the United States Hydrographic Office (Publication No. 128), is designated as the "neutral zone" in which "the direction of the

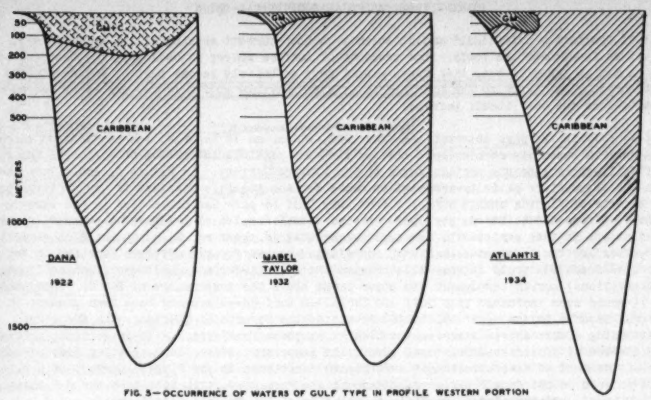

FIG. 5—OCCURRENCE OF WATERS OF GULF TYPE IN PROFILE WESTERN PORTION STRAITS OF FLORIDA ACCORDING TO DANA, MABEL TAYLOR, AND ATLANTIS OBSERVATIONS

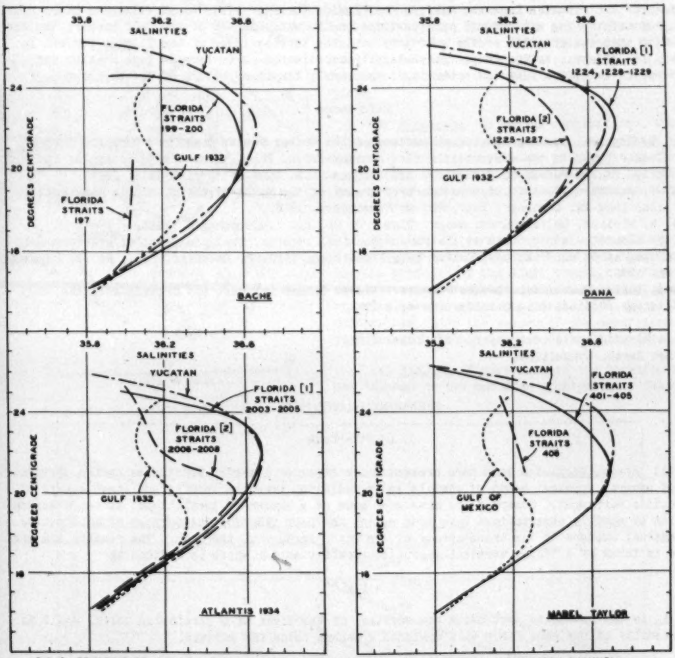

FIG. 6—TEMPERATURE-SALINITY CORRELATIONS, WESTERN PART STRAITS OF FLORIDA AND YUCATAN CHANNEL ACCORDING TO BACHE, DANA, ATLANTIS, AND MABEL TAYLOR OBSERVATIONS, COMPARED WITH AVERAGE CORRELATION-CURVE FOR GULF OF MEXICO PROPER, DETERMINED FROM MABEL TAYLOR DATA (BACHE OBSERVATIONS IN STRAITS OF FLORIDA COMPARED WITH AVERAGE CURVE FOR ALL OBSERVATIONS IN YUCATAN CHANNEL)

current is ordinarily only tidal" and in which a counter-current setting to the westward will sometimes be found near the reefs. The presence of surface-waters of Gulf type in this zone can therefore not be taken to mean that these waters have definitely become part of the outflowing Florida Current, but quite to the contrary it is even possible that they may partly be moving inwards towards the Gulf itself instead.

It is only in the Dana observations from 1922, which, as it happens, are the data on which Nielsen chiefly based his conclusions, that we find any possible indication of an actual admixture of Gulf waters into the surface-layer of the Florida Current. In Figure 6, lower left, we see how the temperature-salinity correlation-curve for the Atlantis stations in the northern part of the Straits of Florida change abruptly from pure Gulf to pure Caribbean type in the temperature-interval from 20° to 22° C, and there were no actual samples of intermediate characteristics obtained at all in this series. In the upper right diagram, however, based on the Dana observations, we see how the temperature-salinity correlation-curves for the northern stations in the Straits of Florida run truly intermediate between the Gulf (1932) and Caribbean (Yucatan Channel, Dana observations) curves throughout its upper range above the temperature of 20° C. From these curves it would seem indicated that Gulf and Caribbean surface-waters may have been present in about equal amounts in the upper 100 to 200 meters of the Straits of Florida, with the mixed layer extending almost entirely across the Straits as shown in Figure 5. It is evident, however, that this state of affairs can only have been quite temporary, since such a limited body of water as that of the Gulf of Mexico could not continue to contribute to the Florida Current at a rate equal to or even on the same order of magnitude as the rate of contribution from the Caribbean Current, without becoming almost immediately exhausted of its endemic waters, which would have to be replaced by a compensating inflow from the Caribbean Current at a rate corresponding to the rate of contribution from the Gulf to the Florida Current. This would eliminate every possibility of maintaining any endemic peculiarities in the water-masses of the Gulf proper, and the very fact that the presence of the Gulf waters in the surface-layer of the Florida Current is clearly recognizable in the temperature-salinity correlation-curve for the Dana station can therefore in itself be taken as evidence of the purely temporary nature of the phenomenon.

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SUBMARINE ILLUMINATION

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(1) Introduction--The data here presented are those of a series of studies on the penetration of several spectral bands of visible solar radiation into the inshore and ocean-waters of the Pacific Northwest. Observations have been made at a number of localities. At two stations a series of monthly observations were made during the year 1934 for the purpose of determining any seasonal changes in the transparency of the water throughout the year. The results are presented in terms of a "total vertical absorption-coefficient" k which is defined by

$$I = I_0 e^{-kx}$$

where I_0 is the intensity just below the surface, of the light of a particular color, and I is the intensity of the same color at a distance x meters below the surface.

This quantity is not, in the true sense, an absorption-coefficient for two reasons: First, the distance x, measured vertically downward, is not the length of light-path in the water since

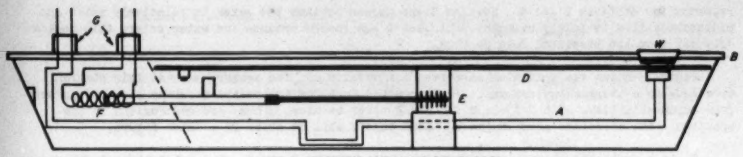

FIG. 1—SCHEMATIC DIAGRAM OF PHOTOMETER

the light does not strike at normal incidence; second, there are several processes involved in decreasing the intensity of the light as it proceeds downward. These are absorption by the water, general and selective absorption by organic and inorganic material, and scattering of light. Consistent and comparable results are obtained by the use of the coefficient defined in this manner.

(2) Apparatus--A calibrated photronic cell is mounted in a steel casting just beneath the glass window. Between the cell and the window, with the least possible clearance, is an aluminum disc mounted on a ratchet-device for rotating the disc. The ratchet is actuated by means of an electromagnet on the deck. There are seven light-filters mounted on the disc in such a way that each one, in turn, can be placed between the window and the cell. The photronic cell yields a relatively large current with low light-intensities and requires no accelerating potential. The current from the cell was measured with a multiple-range microammeter when the casting was in the upper layers of water and with a D'Arsonval marine galvanometer for low light-intensities. A deck-photometer measured the incident light throughout all observations.

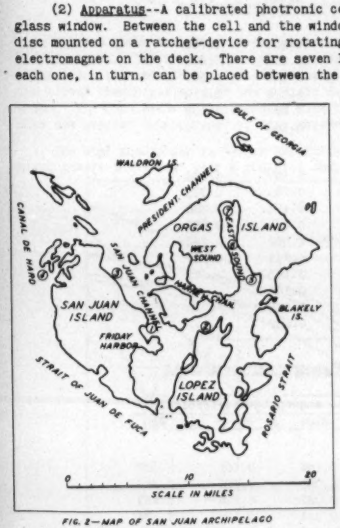

FIG. 2—MAP OF SAN JUAN ARCHIPELAGO

(3) Procedure--In making observations, the submarine photometer was lowered just beneath the surface of the sea, with care to have it as free as possible from any light-influence of the ship. The cell was exposed to the total light and the current recorded.

The light-filters were then successfully placed between the cell and the window, and the current produced by the light transmitted through each filter was recorded. Illuminations at greater depth were obtained and these, with the cell-calibration, give the values of the absorption-coefficients through the use of equation (1)

(4) Results--Figure 2 shows the location of the islands in the San Juan Archipelago. Data are

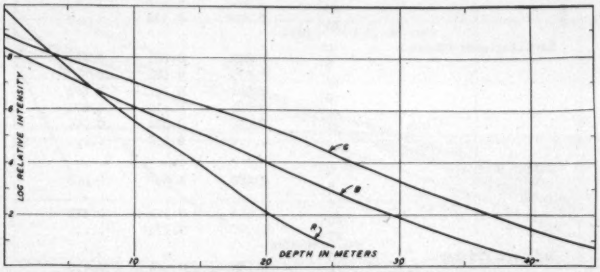

FIG. 3—TRANSMISSION-CURVES FOR STATION 3

reported for stations 3 and 4. Station 3 was chosen because the water is relatively quiet and microscopic life is fairly abundant. Station 4 was chosen because the water enters this region directly from the Strait of Juan de Fuca.

Figure 3 shows the transmission-curves for station 4. The measurements at this station were made on a clear cloudless day. It is noticed that the transmission-curves show a departure from exponentiallity. The letters B, G, and R refer to blue, green, and red regions in the spectrum. The effective wave-length of these colors will be shown in a later figure.

Table 1 shows the absorption-coefficients at stations 3 and 4. The interesting features are that the water at station 4 is considerably more transparent in each spectral region and that the bottom-layers at each station are more transparent than the surface-layers.

Table 1--Values of the absorption-coefficients

Station	Depth	Absorption-coefficients		
		Blue	Green	Red
	meters			
3	0			
	10	0.265	0.207	0.393
	15	0.275	0.208	0.379
	20	0.280	0.223	0.356
	25	0.179	0.210	0.212
	30	0.172	0.206	0.169
	35	0.165	0.188	.....
4	0			
	5	0.232	0.187	0.456
	10	0.215	0.190	0.396
	15	0.187	0.171	0.336
	20	0.213	0.168	0.362
	25	0.233	0.202	0.262
	30	0.216	0.211	0.209
	35	0.163	0.183	.....
	40	0.156	0.184	.....
	45	0.095	0.138	.....
	50	.....	0.089	.....

Table 2--Showing the values of the absorption-coefficient

Station	Depth	Absorption-coefficients		
		Blue	Green	Red
	meters			
Hecate Strait	0			
	10	0.165	0.126	0.407
	15	0.068	0.120	0.414
	20	0.087	0.124	0.287
	25	0.248	0.116	0.104
	30	0.400	0.113	0.051
	35	0.322	0.118	.....
Revillagigedo Channel	0			
	5	0.322	0.231	0.427
	10	0.579	0.231	0.457
	15	0.391	0.351	0.575
	20	0.091	0.410	0.271
	25	0.061	0.234	0.095
	40	.....	0.110	.....
Sumner Strait	0			
	5	0.558	0.397	0.563
	10			
	20	0.256	0.172	0.370
	25	.....	0.171	.....
Off Cape Spencer	0			
	5	0.166	0.168	0.410
	10	0.164	0.169	0.408
	15	0.161	0.167	.....

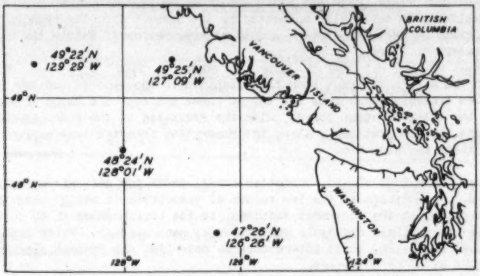

FIG. 4—SHOWING LOCATIONS OF 4 STATIONS IN NORTH PACIFIC OCEAN

Table 2 shows the value of the absorption-coefficients at four stations in the inshore waters of Alaska. The results show that the water in Hecate Strait and in the Gulf of Alaska is more transparent than the inshore waters, especially in the blue region of the spectrum. Hecate Strait has direct communication with the Pacific so that the waters are more nearly those of the open ocean. The Cape Spencer measurements were taken in the Gulf of Alaska outside the Cape and also show the greater transparency of ocean-waters, especially in the blue region.

The high absorption in Sumner Strait is accounted for by the fact that water from the Stikine River enters the Strait over a mud-flat that extends entirely across the mouth of the River from

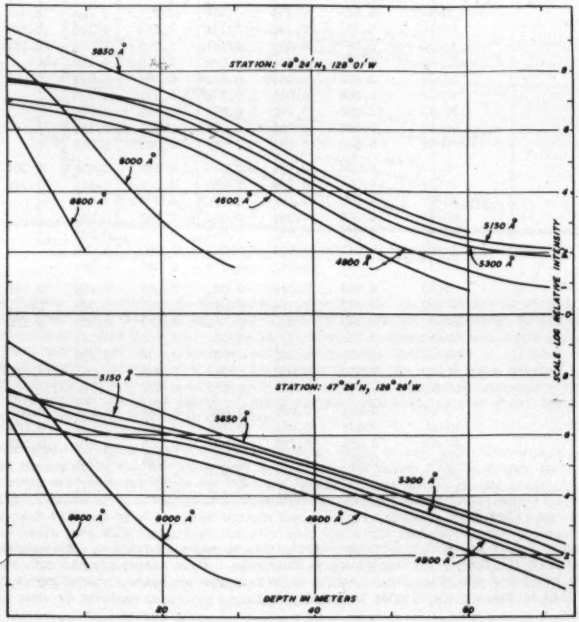

FIG. 5—TRANSMISSION-CURVES FOR TWO STATIONS IN THE NORTH PACIFIC OCEAN

the mainland to Mitkof Island. The ebb makes out from the vicinity of Wrangel through Sumner Strait and its velocity is materially augmented by the current from the Stikine River. The absorption is the greatest between 4 meters and 10 meters. Below 10 meters the transparency is considerably greater.

The dots on the map in Figure 4 show four stations in the Pacific and one in the Strait of Juan de Fuca. The transmission-curves for two of these stations are shown in Figure 5. It will be noticed that the slope of these curves, with the exception of the reds, is considerably less than at any of the inshore stations. Also, the absorption is not a true exponential one for any of the colors, except the deep red.

Table 3 shows the values of the absorption-coefficients for each of seven bands at each of the five stations. In addition to the low values of absorption it may be seen that there is an increase in absorption, at the outermost stations, in the neighborhood of 40 to 50 meters. Samples of the water and vertical net-hauls were taken at each station. While analysis of the net-hauls have not been completed, it is interesting to note that the richest plankton-hauls were made between depths of 30 to 50 meters.

Table 3--Spectral absorption-coefficients

Station	Depth	Total vertical absorption-coefficient per meter at depth in meters						
		4600	4800	5150	5300	5650	6000	6800
	meters							
Strait of Juan de Fuca	0- 5	0.434	0.388	0.320	0.294	0.344	0.482	
	5-15	0.412	0.374	0.328	0.292	0.290	0.452	
	15-20	.....	0.332	0.274	0.266	0.248	0.354	
49° 25'	0-10	0.202	0.174	0.149	0.144	0.206	0.385	0.574
127 09	10-15	0.138	0.170	0.136	0.170	0.166	0.304	
	15-20	0.137[a]	0.096	0.144	0.090	0.108	0.284	
	20-25	0.060	0.064[a]	0.088	0.092	0.132		
	25-30	0.059[a]	0.060[a]	0.073[a]	0.080	0.074		
	30-35	0.058	0.048	0.072[a]	0.071	0.096		
	35-40	0.058	0.072	0.071	0.068	0.096		
	40-45	0.024	0.026	0.072	0.040	0.140		
	45-50	0.040	0.036	0.080	0.086	0.084		
49° 22'	5-10	0.104	0.054	0.046	0.062	0.116	0.306	0.570
129 29	10-20	0.091	0.086	0.093	0.105	0.110	0.286	
	20-30	0.079	0.065	0.070	0.076	0.091		
	30-40	0.059	0.084	0.090	0.083	0.092		
	40-50	0.071	0.062	0.043	0.072	0.066		
	50-60	0.047	0.053	0.055	0.060	0.096		
	60-70.5	.....	0.063	0.070	0.089	0.089		
48° 24'	0-10	0.054	0.018	0.033	0.037	0.100	0.249	0.451
128 01	10-20	0.041	0.064	0.035	0.060	0.083	0.291	
	20-30	0.130	0.099	0.105	0.106	0.109	0.156	
	30-40	0.162	0.170	0.146	0.146	0.149		
	40-50	0.104	0.101	0.097	0.106	0.118		
	50-60	0.118	0.069	0.085	0.083	0.095		
	60-72.5	.....	0.032	0.030	0.027	.....		
47° 26'	0-10	0.081	0.088	0.063	0.094	0.148	0.338	0.488
126 26	10-20	0.047	0.041	0.056	0.049	0.103	0.226	
	20-30	0.058	0.039	0.055	0.055	0.076	0.167	
	30-40	0.087	0.099	0.065	0.089	0.097		
	40-60	0.090	0.081	0.079	0.086	0.081		
	60-72.5	0.105	0.081	0.082	0.095	0.103		

[a]Weighted mean.

For comparison, a table of absorption-coefficients is shown in Table 4. The values of other observers were obtained by interpolation of their data. It is interesting to note the decrease in transparency starting with Hulburt's value for pure sea-water, proceeding to the open ocean, and then to inshore and finally to inland lakes.

Table 4--Comparison of absorption-coefficients

Observer, range, method	Total vertical absorption-coefficient per meter at depth in meters						
	4600	4800	5150	5300	5650	6000	6600
Hulburt 0 to 4 meters Spectrophotometer	0.0166	0.0154	0.018	0.024	0.052	0.165	
Utterback and Jorgensen Average of deep-sea stations	0.085	0.073	0.069	0.079	0.100	0.253	0.503
Utterback and Jorgensen Station 49° 25' N and 127° 09' W	0.104	0.093	0.106	0.093	0.122	0.279	0.574
Atkins and Poole Internat. Hydrographic Station E-1	0.143	0.146	0.154	0.157	0.163	0.224	
Utterback and Jorgensen[a] Thatcher Pass, San Juan Islands	0.336	0.316	0.258	0.256	0.288	0.441	0.593
Erikson Gunflint Lake, Minnesota	0.820	0.610	0.437	0.390	0.321	0.330	

[a]Unpublished data.

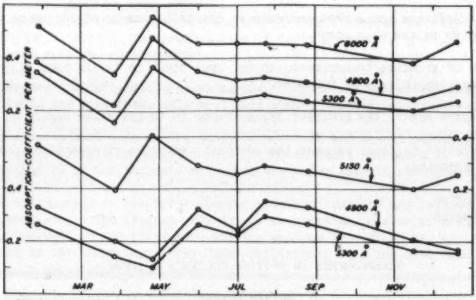

FIG. 6—CURVES SHOWING VARIATION IN ABSORPTION-COEFFICIENT DURING 1934 NEAR CAPE FLATTERY

Figure 6 shows the variation in the absorption-coefficient in the Strait of Juan de Fuca throughout the year 1934. The station in the Strait (Pillar Point) was located in mid-channel about 25 miles in from Cape Flattery. It is at the head of a submarine chasm which extends out from the Strait and through the continental shelf. Beyond the shelf there is evidence of upwelling of surface-waters. This upwelled water is carried through the chasm where general turbulence is produced by tidal and non-tidal currents on the shelf. This causes considerable mixing of the water. At this station the upper layers of water are more characteristic of Puget Sound water, while the lower layers are oceanic in character.

The four upper curves of Figure 6 show the average value of the absorption-coefficients for the first 10 meters while the two lower ones are the average values from 10 meters to 20 meters. Only those bands are shown for which the data are complete. The values of the coefficients are lower than for inshore water. The general variation is an increase in transparency in the early part of the year followed by a decrease through March, April, and May, with a minimum in June. Vertical net-hauls were made throughout the year and, while the contents of the net-hauls have not been analyzed, the period of maximum growth in the Strait is that of the lowest transparency of the waters, that is, in June. Monthly observations have been made at three other stations in Puget Sound during 1934. A complete report of these will appear soon in the literature, as will observations made in Portland Canal, in southwestern Alaska, in the late summer of 1934.

It is desirable to point out some of the uncertainties in submarine illumination-observations.

The chief ones are due to changing surface-conditions which affect the light reflected from the water and the changing content of the water above the photometer while measurements are being made. Both of these uncertainties can be reduced in magnitude by completing a set of observations in the least possible time. The photometer permitted of very rapid observations. The illumination produced by the light transmitted by each of the seven filters could be measured in less than two minutes, thus insuring a minimum change in the water above the photometer.

The variation in the transmission-bands of the filters is a source of uncertainty because the absorption of the water is greater in the extreme ends of the spectrum than in the middle portion. Thus the effect of absorption with increasing depth for a red filter is to cut off the transmission-band on the long wave-length side. The reverse is true for the blue filters. This results in the "effective wave-length" of any filter shifting toward the center of the spectrum as the length of the light-path becomes greater, unless the "effective wave-length" happens to be that of least absorption by the water. The transmission-bands of each filter were relatively narrow and the wave-length assigned to each is to be considered as designating a narrow, but not quite constant, region of the visible spectrum.

The effect of the ship when the photometer is near the surface may be considerable. While making observations, the ship was always kept opposite the Sun. Except in the summer months, the observations were made with well diffused and quite constant surface-illumination.

(5) Conclusions--(a) Several hundred total vertical absorption-coefficients have been determined for Pacific Northwest waters. These are found to be good indices of the transparency of the water.

(b) There is a definite and marked increase in the transparency of the water as one proceeds from the inshore water to the open ocean.

(c) The region of greatest transparency in the open ocean is in the blue region of the spectrum on the long wave-length side of the blue.

(d) In the inshore waters the greatest transparency is in the green region of the spectrum.

(e) Some correlation is found between the seasonal variation of absorption-coefficients and seasonal growth of organisms.

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OCEANOGRAPHY IN BRITISH COLUMBIA IN 1934

C. McLean Fraser

As in previous years, most of the work in oceanography in British Columbia in 1934 was carried on in connection with the activities of the Biological Board of Canada, at the two main stations, Nanaimo and Prince Rupert, and several subsidiary field-stations for special investigations in different parts of the province. In this work, as usual, the Board has had the cooperation of several members of the staff in the science departments of the University of British Columbia. Voluntary workers from several other institutions have also contributed materially. There were 18 members of the regular staff on the two stations and 22 voluntary workers. Still others contributed by working on material supplied from the stations.

During the year, 59 papers were published. The nature of the researches may be considered by treating them under the three heads: (1) Chemical and physical oceanography; (2) biology and fisheries; (3) fisheries technology.

Physical and chemical oceanography--Little additional field-work has been done in the Strait of Georgia, but the study of data previously obtained has been continued.

Through the courtesy of the Hydrographic Service, accommodation for two members of the staff of the Nanaimo station was provided on board the excellently equipped survey ship, the Wm. J. Stewart, from April 15 to August 1, 1934, to commence a program of oceanographic investigation on the west coast of Vancouver Island. Analyses were made for chlorides, dissolved oxygen, silicates, phosphates and nitrites, and temperatures, densities, and pH readings were taken. Particular attention was given to tidal and other currents and hydrodynamic studies were made.

Through the courtesy of H. D. Parizeau, Officer-in-Charge of the Survey, access was given to the original charts on which soundings were recorded, and from these a chart has been prepared showing the interpretation of these soundings into contours of the sea-bottom, for about 25 miles offshore, for a distance of 125 miles.

Temperature-, chlorinity-, and pH-readings of the sea-water at various depths have been continued in several localities. To the previous list Prince Rupert Harbour has now been added.

The transpacific liners are taking readings, as they have been doing for some time. The Meteorological Office in Toronto is correlating these readings. This work will soon be completed to the end of the year 1934.

The Wm. J. Stewart was used in the Hydrographic service during the year. Most of the survey work during the year was carried on off the coast of Vancouver island.

Biology and fisheries--The extensive program for the investigation of the relative efficiencies of natural and artificial propagation of sockeye salmon is now nearing conclusion. In connection with this program, such matters as the factors involved in the high mortality of young sockeye in Cultus Lake, the returns from the sea, the efficiency of "eyed" egg planting, pond retention of young sockeye salmon, utilization of landlocked sockeye salmon eggs for increasing sockeye runs from the sea, and transplantation have been receiving attention. The study of the annual samplings of the sockeye salmon run to Fraser, Skeena, and Naas rivers, and Rivers Inlet, was made as usual. A study of natural propagation and transplantation of pink salmon in the Queen Charlotte Islands has been begun.

Statistical analyses of the pilchard and the herring fisheries have been continued and population-studies of herring, the productivity of herring spawning grounds, and the food of young herring have received consideration.

Information has been obtained concerning the life-history of some of the species of fish of minor importance in the fisheries, eulachon, surf smelt, anchovy, and capelin.

Some progress has been made on the study of nematode and acanthocephalan parasites of Pacific fishes. An investigation has been made of the economic relations of water fowl to obtain an accurate evaluation of the economic status of the water fowl in relation to the fisheries.

Oyster investigations on the three species (native, eastern, and Japanese) in British Columbia have been continued. The feeding activity of the Japanese oyster in relation to tidal currents has been included in the field-work and the anatomy and physiology of the native and the Japanese oysters in the laboratory work. Some exploratory work has been done in an attempt to locate scallops in commercial quantities.

The crab investigations have been carried far enough to draw definite conclusions as to age, moulting, spawning, and other life-history features. The early life-history of various species has been worked out.

In the investigation of marine wood-borers, the time of greatest infestation, as well as the incidence, at various depths, and correlation of these with physico-chemical data have received attention.

The comparative food-values of various species of fish have been investigated.

In connection with the work on the Wm. J. Stewart on the west coast of Vancouver Island, biological investigation was carried on. Plankton was collected at definite vertical depth-intervals, where the physical and chemical data were also obtained. Several useful modifications of mechanical devices used in this work were developed. Samples of the bottom-fauna were obtained by dredge and beam-trawl, and extensive shore-collections were made when the state of the tide permitted. The material was taken to the Nanaimo Station and sorted out, but, as yet, only a small portion of it has been critically examined.

Faunistic studies have been made on dinoflagellates, trematode parasites, polychaetes, copepods parasitic on fish, mollusca, and marine fishes of British Columbia, and on the hydroids, crabs, and cephalopods of the Stewart collection.

Miscellaneous investigations included: The dissolved nitrogenous materials in the effluent of reduction plants; the biochemistry of the crystalline style in clams; a comparison of the

nervous system in three species of barnacles; a blood picture of two species of fish in relation to the presence of intestinal parasites and bacteria; the changes taking place in beef liver during storage under various conditions--as beef liver is used in large quantities for feeding young fish in rearing ponds; two methods for the determination of chloride in the presence of phosphate in the analysis of fish products.

Fisheries technology--The conclusion as to relative efficiencies of roof-tank refrigeration-units as compared with the standard end-tanks, in maintaining a low and uniform temperature, that had been tested out in a small-scale refrigerator-car, was confirmed by making use of actual refrigerator-cars. Further experiments on improved utilization of the refrigerating medium have been carried out in the small-scale car. Insulation and a critical rate of freezing has come up for consideration.

Very successful results have been obtained by the introduction of formaldehyde disinfectant treatment for halibut fishing-vessels and efforts have been made to extend its use to the deodorizing of railway refrigerator-cars. Further bacterial studies have been made in connection with freezing processes. Methods of preventing "rusting" or red discoloration of frozen fish in cold storage and of cracking of the ice-glaze, have been developed. Bacteriological testing in connection with improving process treatment in canning of crabs, clams, and shrimps has given good results.

Improved methods of reduction and utilization of fish oils for commercial and medicinal purposes has continued to be one of the major features of chemical investigations. Experiments on the properties of paint films, prepared from fish oil, before and after bodying and treatment with driers have been brought to a satisfactory conclusion. Experimental work on the hydrogenation of fish oils for commercial purposes has been largely suspended in order that a mathematical treatment of the changes in composition undergone during hydrogenation may be completed. When this is complete, the experimental work will be resumed. The investigation of fish oils as a source of vitamins has been vigorously continued, and the blending of certain fish oils has produced a very satisfactory product. The variation in the vitamin-content in oil from the same species at different times of the year, better methods of extraction, determination of vitamin potency, are all receiving attention. Biological assays of vitamin-A potency are expensive and chemical assays are not satisfactory. A spectrophotometric method has been considered and is being investigated.

Some characteristics of the juices producing "curd" (coagulated protein juices) in canned salmon were determined and means of preventing curd were investigated.

The nature of the pigments in salmon-body oil has been studied and a suggested chemical structure is being confirmed by spectrophotometric methods.

Experiments on the salting of herring have been continued, and in that connection a comparison of methods of determining chlorides in fish ash was carried out.

[Note: Most of the information for this report was obtained from the annual report of the Director of the Nanaimo Station, Dr. W. A. Clemens, and the similar report of the Director of the Prince Rupert Station, Dr. N. M. Carter.]

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SUMMARY OF THE OCEANOGRAPHIC INVESTIGATIONS OF BERING SEA AND BERING STRAIT

Clifford A. Barnes, Thomas G. Thompson, and F. A. Zeusler

The present paper is a summary of the oceanographic investigations conducted in Bering Sea during the summer of 1934 in a cooperative program of study between the United States Coast Guard and the Oceanographic Laboratories of the University of Washington.

Description of region--Bering Sea, second only to the Mediterranean Sea in size, covers an area of 878,000 square miles. It extends from a latitude of 52° north to the Arctic Circle and from 160° west to 160° east longitude and is bounded on the south by the Alaskan Peninsula and the Aleutian Islands, on the east by Alaskan coast-lines, and on the west by the Siberian Coast. On the north, it is connected with the Arctic Ocean by means of Bering Strait, a narrow channel of water about 40 miles in width and having a depth of from 20 to 30 fathoms.

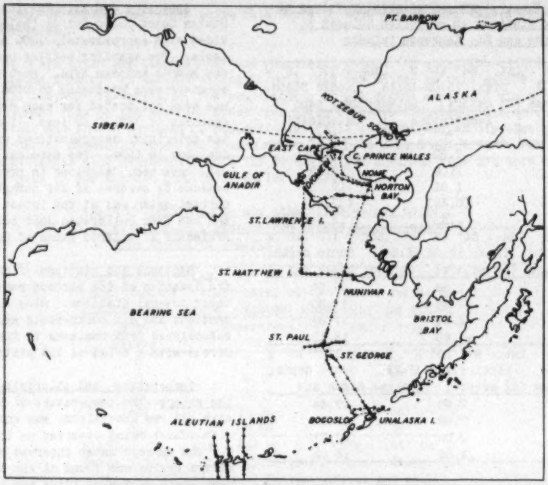

FIG. 1—MAP OF REGION SHOWING SECTIONS AND STATIONS OCCUPIED

The Aleutian chain of islands and the Aleutian Ridge which extend westward for 1200 miles from the Alaskan Peninsula to within a comparatively short distance of the Asiatic mainland, form a partial barrier between the North Pacific Ocean and Bering Sea. The islands are of volcanic origin and some of the peaks are still active. North of the Aleutian Ridge, the bottom of Bering Sea drops abruptly to a depth of about 2000 fathoms, the 1000-fathom contour being, in some instances, within a few miles of the islands. South of the islands, the bottom of the North Pacific slopes more gradually but drops to much greater depths, reaching a maximum of 4000 fathoms in the Aleutian Trough. Tidal currents set through the various passes between the islands in a northerly or northeasterly direction on the flood-tide and, with an ebb-tide, follow a southerly or southwesterly direction. Velocities as great as 9 knots are sometimes observed in the passes (U.S. Coast Pilot, Alaska, pt. II, p. 304, 1931). The passes in the entire Aleutian Chain vary in depth from 15 or 20 fathoms to more than 300 fathoms, and thus provide paths for free circulation of the surface-waters of Bering Sea and the North Pacific. However, the Aleutian Ridge prevents any exchange of the abysmal waters. Between Attu Island and the Komandorski Islands, depths of 2000 fathoms have been recorded, thus providing a means for the exchange of the deeper waters. Bering Strait prevents any exchange of the waters of the Arctic Ocean and thus produces conditions in Bering Sea and the North Pacific that are not encountered in the North Atlantic.

Three great rivers, the Yukon and Kuskokwim in Alaska and the Anadir in Siberia, discharge into the northern waters of Bering Sea. The basin of Bering Sea is approximately divided into two equal portions by the 100-fathom contour which extends from Unimak Pass, in a northwesterly direction, to Siberia, passing just south of the Pribilof Islands. The sea-floor, east and north of this contour, is an immense plateau of little changing depth, averaging between 20 and 30 fathoms and shoaling gradually toward the coast-lines. West and south of the contour, the sea-floor drops more or less rapidly to a basin approximating a depth of 2000 fathoms.

The weather of Bering Sea is notoriously bad. During the fall, winter, and spring months, storms are frequent and severe, especially along the Aleutian chain. In the summer months, the Bering is almost continuously enveloped in fog which is dispersed somewhat by the heavy winds of September.

Ice generally covers Bering Sea north of the Pribilof Islands and Bristol Bay during the winter months, but there may be considerable seasonal variation. This ice invariably moves northward, unless influenced by adverse winds. The movement generally begins in April, the ice breaking along the Siberian Coast. Bering Strait may not be free of ice until the first week in July.

Table 1--Temperature and chlorinity-values at three stations in a section between St. Matthew and St. Lawrence islands

Station: 71 Lat.: 64° 25' N Long.: 172° 12' W Date: 8-6-34 Time: 15:00-15:18 Sonic Depth: 36 fathoms (66 meters) Bottom: Gray sand		
Depth meters	Temperature °C	Chlorinity o/oo
0	7.80	17.34
10	7.00	17.38
25	1.81	17.72
(35)	(0.44)	(17.85)
50	-1.60	18.06
Station: 72 Lat.: 64° 15' N Long.: 172° 12' W Date: 8-6-34 Time: 16:03-16:24 Sonic depth: 34.5 fathoms (63 meters) Bottom: Black mud		
0	7.98	17.30
10	7.85	17.30
25	1.91	17.81
50	-1.63	18.15
Station: 73 Lat.: 64° 05' N Long.: 172° 13' W Date: 8-6-34 Time: 17:06-17:24 Sonic depth: 34 fathoms (62 meters) Bottom: Black mud		
0	7.93	17.44
10	7.89	17.52
25	2.00	17.77
50	-1.56	18.05

Apparatus and methods--The United States Coast Guard Cutter Chelan was provided with approximately 1000 meters of cable. The sampling bottles used were of the Nansen-Knudsen type. Most of the thermometers were graduated to 0°05 C. and all had been calibrated for each degree to an accuracy of 0°01 C or less. The error of the chlorinity determinations was less than one part in 1500. The chemical methods used have been described in previous publications by several of the authors. The current-meter was of the latest Ekman type and had been calibrated just before use by Professor V. Walfrid Ekman of Lund, Sweden.

Sections and stations--Figure 1 shows the location of the various sections with their several stations. Nine east-west sections and six north-south sections were established from Unalaska to the Arctic Circle with a total of 120 stations.

Temperature- and chlorinity-values of the waters--The temperature of the waters, with but few exceptions, was under 10° C, with values being observed as low as -1°6 C. The warmest water observed during the entire cruise was found at the Nome anchorage, where values of 10°88 and 10°78 C were obtained at the surface and 10 meters, respectively. The coldest water was found in the bottom-layers between St. Matthew and St. Lawrence islands (see Table 1). At three consecutive stations in this section, where the bottom was about 60 meters, temperatures that varied between -1°56 to -1°63 C were obtained at depths of 50 meters, the corresponding surface-temperatures varying from 7°80 to 7°93 C. At these stations there was a very rapid drop in temperature of the waters between 10 and 25 meters. Thus, for most of the central and western portion of Bering Sea, north of St. Paul Island, the waters appear to be divided into two distinct thermal layers. The warmer layer was characterized by chlorinity-values that were much lower than the colder waters.

At the deep stations in the section between Bogoslof Island and St. George Island--illustrations of which are given in Table 2--the temperatures gradually decreased with depth to 200 meters where minimum values were noted. Below 200 meters, there was an increase in temperature at 300

Table 2--Temperature- and chlorinity-values at two stations in a section between Bogoslof and St. George islands

Station: 105 Lat.: 54° 03' N Long.: 168° 02' W Date: 8-20-34 Time: 17:32-18:45 Sonic depth: 800 fathoms (1460 meters) Bottom:			Station: 106 Lat.: 54° 22' N Long.: 168° 17' W Date: 8-20-34 Time: 20:38-21:57 Sonic depth: 780 fathoms (1425 meters) Bottom:		
Depth meters	Temperature °C	Chlorinity o/oo	Depth meters	Temperature °C	Chlorinity o/oo
0	9.64	18.31	0	10.15	18.23
10	8.74	18.31	10	9.40	18.26
25	7.35	18.37	25	8.41	18.27
50	5.34	18.42	50	4.61	18.40
75	4.19	18.47	75	4.05	18.48
100	3.89	18.48	100	3.78	18.52
150	3.40	18.52	150	3.48	18.54
200	2.97	18.53	200	3.33	18.58
300	3.27	18.64	300	3.46	18.67
400	3.48	18.76	400	3.41	18.79
500	3.35	18.81	500	3.33	18.86
600	3.27	18.89	600	3.22	18.93
800	3.03	18.96	800	3.00	18.98
1000	2.83	18.94	1000	2.77	19.03

meters, followed by gradual decreases below this depth to 1000 meters when values approximating 2°80 C were obtained.

In Table 3 are given the temperature- and chlorinity-values for a section of four stations run across Bering Strait. It is interesting to note that the waters in this narrow area showed a considerable temperature-variation. The temperatures at all depths were much higher on the Alaskan side of the Strait than on the Siberian side. The surface- and bottom-temperatures at the most easterly station were 7°27 C and 5°89 C, respectively, while the most westwardly station, near the Siberian Coast, showed surface- and bottom-temperatures of 2°34 C and 1°02 C, respectively. The chlorinity-values also demonstrate that the waters on the Siberian side are more concentrated than those on the Alaskan portion of Bering Strait.

Table 3--Temperature- and chlorinity-values at four stations in a section run across Bering Strait from Alaska to Siberia

Depth meters	Temperature °C	Chlorinity c/oo
Station: 36	Lat.: 65° 54' N	Long.: 168° 21' W
Date: 7-31-34	Time: 16:21-16:49	Sonic depth: 30 fathoms (55) meters
Bottom: Black clay and gravel		
0	7.27	17.28
10	6.17	17.57
25	6.11	17.58
(40)	(5.95)	(17.58)
45	5.89	17.58
Station: 37	Lat.: 65° 55' N	Long.: 168° 42' W
Date: 7-31-34	Time: 17:31-18:01	Sonic depth: 29 fathoms (53 meters)
Bottom: Gravel and shell		
0	7.45	17.36
10	2.63	17.77
25	2.70	17.83
(40)	(2.68)	(17.84)
45	2.68	17.84
Station: 38	Lat.: 65° 56' N	Long.: 169° 05' W
Date: 7-31-34	Time: 18:45-19:20	Sonic depth: 29 fathoms (53 meters)
Bottom: Snale and rock		
0	6.71	17.49
5	4.31	17.60
10	1.32	17.85
20	1.23	17.85
25	1.28	17.85
40	1.18	17.86
Station: 39	Lat.: 65° 54' N	Long.: 169° 32' W
Date: 7-31-34	Time: 20:06-20:27	Sonic depth: 29 fathoms (53 meters)
Bottom: Coarse gravel		
0	2.34	18.05
5	1.20	18.08
10	1.15	18.09
15	1.12	18.09
25	1.13	18.10
(40)	(1.04)	(18.11)
43	1.02	18.11

The chlorinity-values were higher for the surface-waters of the southern portion of Bering Sea and gradually decreased as Bering Strait was approached. The values obtained varied from about 18.00 o/oo in the south to about 17.40 o/oo in the north. This general decrease is explained by the discharge of the large rivers, the Yukon and Kuskokwim in Alaska and the Anadir in Siberia. The discharge of the Yukon, which drains over 330,000 square miles of territory, was readily noticeable one hundred miles from the delta. Evidences of considerable upwelling and turbulence in the northwestern part of Bering Sea explain the more concentrated sea-water which existed in the Siberian portion of Bering Strait, while the waters diluted by the Yukon River explained the less concentrated sea-water in the Alaskan portion.

Nutrient salts and dissolved oxygen--As in the case of the temperature- and chlorinity-values, no attempt will be made to present in this paper all of the data obtained showing the

concentrations of the nutrient salts and dissolved oxygen in the various stations occupied in the 15 sections. Tables 4 and 5 are illustrative of the data secured. Table 4 gives the data for phosphates, silicates, nitrites, and dissolved oxygen, expressed as milligram-atoms of the characteristic element, per kilogram of water. The concentrations of phosphates and silicates in the surface-waters are considerably higher than similar values obtained in southern portions of the North Pacific Ocean. The nitrite-values are normal, nitrites being present in the waters above 50 to 200 meters and absent below these depths. Evidence of a zone of minimum oxygen, as discussed in a previous paper (Thompson, Thomas, and Barnes, James Johnstone Memorial Volume, pp. 203-234, 1934), are indicated, but it is to be regretted that the sampling cable was not of sufficient length to obtain samples at greater depths. However, the low oxygen-values are similar to those obtained in the North Pacific and are the values that so definitely distinguish and characterize the waters of Bering Sea and the North Pacific from those of the North Atlantic.

Table 4--Concentration of phosphates, silicates, nitrites, and dissolved oxygen at two stations in a section between Bogoslof Island and St. George Island (Concentrations are expressed as milligram-atoms of the characteristic element per kilogram of sea-water)

Station	Depth meters	Phosphorus mg-atom x 10^3	Silicon mg-atom x 10^2	Nitrite nitrogen mg-atom x 10^4	Dissolved oxygen mg-atom	Dissolved oxygen o/o sat.	pH
105	0	1.73	3.0	0.6	.581	103.2	8.1
	10	1.73	3.5	0.6	.581	101.4	8.1
	25	1.83	4.0	0.6	.566	95.9	8.1
	50	2.05	5.0	2.0	.522	84.5	8.1
	75	2.21	6.0	0.9	.493	77.8	8.05
	100	2.21	6.5	0.4	.484	75.7	8.05
	150	2.37	7.0	0.2	.474	73.4	8.05
	200	2.52	7.5	0.0	.459	70.3	8.05
	300	2.84	8.0	0.0	.315	48.7	8.00
	400	2.84	9.0	0.0	.159	24.8	7.95
	500	2.84	10.0	0.0	.129	20.0	7.9
	600	2.84	10.0	0.0	.089	13.8	7.9
	800	2.84	12.0	0.0	.058	9.0	7.9
	1000	2.84	13.0	0.0	.078	12.0	7.9
106	0	1.48	3.3	0.3	.494	88.5	8.1
	10	1.51	3.5	0.5	.549	97.2	8.1
	25	1.70	3.5	0.8	.555	96.0	8.1
	50	2.21	6.0	2.2	.428	68.0	8.1
	75	2.37	6.5	0.0	.395	62.1	8.05
	100	1.83	7.0	0.0	.389	60.3	8.05
	150	1.89	8.0	0.0	.359	55.7	8.05
	200	2.52	8.0	0.0	.390	60.3	8.00
	300	2.68	9.0	0.0	.229	35.6	7.90
	400	2.68	9.0	0.0	.150	23.3	7.90
	500	2.78	11.5	0.0	.089	13.8	7.75
	600	2.78	11.5	0.0	.072	11.1	7.75
	800	2.78	11.5	0.0	.058	9.0	7.75
	1000	2.78	12.0	0.0	.049	7.5	7.70

In some of the sections (data not given in this paper), maximum oxygen-concentrations were observed at 25 meters, this maximum being very marked at stations where two very distinct thermal layers were in evidence. Likewise, in such waters, the nitrite-values were very unusual, the warmer surface-layers showing complete absence of nitrites and the bottom colder layers showing a considerable but varying concentration of nitrites. This is illustrated by the data given in Table 5.

The waters of Bering Strait showed concentrations of the nutrient salts that were considerably lower than those observed at stations in the most southerly sections of Bering Sea. The station nearest Alaska in Bering Strait showed concentrations of phosphates and silicates that were much lower than at the station nearest Siberia. No nitrites were found at any depth at the Alaskan station while quantities of nitrites were present at all depths at the Siberian station. The concentration of the dissolved oxygen was much greater for the station nearest Alaska than for the one nearest Siberia.

The two intermediate stations in Bering Strait differ from the ones near the coasts of Alaska and Siberia in that the phosphate concentration is lower for the surface-waters but con-

siderably higher for the deeper waters. No nitrites exist in the surface-waters but they occur in the deeper. In general, the concentration of silicates increases and the dissolved oxygen decreases from east to west.

Table 5--Concentration of phosphates, silicates, nitrites, and dissolved oxygen at the four stations in the section across Bering Strait from Alaska to Siberia (Concentrations are expressed as milligram-atoms of the characteristic element per kilogram of water)

Station	Depth meters	Phosphorus mg-atom x 10^3	Silicon mg-atom x 10^2	Nitrite nitrogen mg-atom x 10^4	Dissolved oxygen mg-atom	Dissolved oxygen o/o sat.	pH
36	0	0.22	0.5	0.0	.682	113.6	8.2
	10	0.57	0.5	0.0	.616	100.5	8.15
	25	0.57	0.5	0.0	.620	101.0	8.1
	(40)	(0.73)	(0.5)	(0.0)	(.613)	(99.3)	(8.1)
	45	0.79	0.5	0.0	.610	98.9	8.1
37	0	0.32	1.0	0.0	.671	112.2	8.20
	10	1.26	3.0	0.4	.567	85.1	8.15
	25	1.26	1.5	0.4	.565	85.0	8.15
	(40)	(1.33)	(2.0)	(0.4)	(.563)	(84.6)	(8.15)
	45	1.35	2.2	0.4	.562	84.5	8.15
38	0	0.13	0.2	0.0	.679	111.9	8.2
	5	0.32	0.2	0.0	.828	129.2	8.2
	10	1.42	3.0	0.7	.619	90.0	8.2
	20	1.42	2.5	0.9	.609	88.3	8.2
	25	1.26	2.5	0.8	.558	85.5	8.2
	40	1.26	2.5	0.8	.558	85.3	8.2
39	0	0.63	2.0	0.9			8.10
	5	0.79	2.5	1.0	.634	92.3	8.10
	10	0.79	2.5	1.0	.568	82.4	8.05
	15	0.79	2.5	1.0	.549	79.7	8.05
	25	0.88	2.8	1.0	.590	85.6	8.05
	(40)	(0.94)	(3.0)	(1.0)	(.588)	(85.2)	(8.05)
	43	0.95	3.0	1.0	.587	85.1	8.05

Currents--In the nine east-west sections established by the Chelan from Unalaska to the Arctic Circle, calculations from the fundamental data showed a general northward trend to the water-movement. The currents were most pronounced along the Aleutian Ridge and through Bering Strait. Minimum current-values were obtained in the regions of the Pribilof Islands and St. Matthew Island. The two north-south sections near the Aleutian Ridge gave resultant currents that were analogous to those calculated from the data obtained in the cooperative study of the Hydrographic Office of the United States Navy and the Oceanographic Laboratories of the University of Washington during the summer of 1933, that is, an easterly trend of the currents in the immediate vicinity of the island chain reversing to a westerly direction about 40 miles offshore. There was a pronounced westerly set just south of the Pribilof Islands, attaining a maximum of about 0.2 knot. From St. Paul Island northward to Nome and between St. Matthews and St. Lawrence islands, the westerly set was of the order of a few hundredths of a knot but gave way to a slight easterly trend between a few stations.

In Bering Strait, a section of four stations established ten miles apart was run from a point near the Alaskan coast to one near the coast of Siberia, the fundamental data being given in Table 3. The calculated currents are shown in Table 6.

To check the calculated resultant currents and to note tidal effects, the Chelan was anchored for a period of 24 hours midway between East Cape, Siberia, and Big Diomede Island. Direct current-observations were made every three hours with an Ekman current-meter at five different depths (surface, 5, 10, 25, and 40 meters), the Chelan being anchored in 47 meters of water. Throughout the entire cycle, the currents all showed a northerly trend and varied from 0.3 to 0.7 knot and showed little variation in intensity with depth. The data are given in Table 7 for the complete cycle.

In the general theoretical considerations upon which the method for calculating currents from fundamental physical and chemical data is based, the currents of the upper water-layers are

Table 6--Resultant currents calculated from the fundamental data given in Table 3

Depth	Station: 36-37; K = 8.75			Station: 37-38; K = 8.29			Station: 38-39; K = 7.16		
meters	$\Delta D \times 10^5$	$\Delta H \times 10^5$	Knot	$\Delta D \times 10^5$	$\Delta H \times 10^5$	Knot	$\Delta D \times 10^5$	$\Delta H \times 10^5$	Knot
0	0	2663	0.23	0	437	0.04	0	1863	0.13
5	...	....	....	...	...	....	517	1346	0.10
10	355	2308	0.20	197	240	0.02	823	1040	0.07
25	1323	1340	0.12	437	0	0.00	1338	525	0.04
40	2328	335	0.03	...	...	....	1863	0	0.00
45	2663	0	0.00	...	...	....	....	...	....

Notes: Positive values indicate currents setting north; negative values indicate currents setting south. Mean latitude: 65° 55' N. K is a constant for any given pair of stations. It involves the mean latitude, distance between stations, and conversion-factor to change metric units to knots. $\Delta D \times 10^5$ is the difference in dynamic depth (dynamic meters x 10^5) of the waters at the same linear depth at two consecutive stations. $\Delta H \times 10^5$ is the difference in the height of the observed water-level above the lowest common sampling level of two consecutive stations; these differences in height are expressed in dynamic meters x 10^5. Knot gives the resultant current at the several depths in reference to the lowest depth as zero.

given in reference to the lowest observed level, where it is assumed that there is no movement of the water, or, in other words, the current near the bottom is taken as zero. Now, if the average value of the bottom-currents observed with the Ekman current-meter is taken in place of zero, as the reference for calculations, then a fairly good agreement is obtained between calculated and observed values as may be seen from Table 7.

Table 7--Observed and calculated currents from data during 24 hours at station midway between East Cape and Big Diomede Island

Depth	Average observed current	Average calculated current
meters	knot	knot
0	0.39[a]	0.59
5	0.51	0.58
10	0.50	0.53
25	0.54	0.50
40	0.46	(0.46)

[a]Because of the shielding effect of the ship, the current-values obtained at the surface by direct observations should be discounted.

From the average depth of Bering Strait, the distance at its narrowest part and the data given above, it is calculated that Bering Sea discharges one cubic nautical mile of water every two hours through Bering Strait. It is interesting to compare this value for the current in Bering Strait with that for the Gulf Stream at its narrowest point off the coast of Florida, as calculated by Wüst who obtained 14 cubic nautical miles per hour. In contrast to these values is the average hourly discharge of the Mississippi River, equivalent to about 0.03 cubic nautical mile.

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A MARINE CORING INSTRUMENT--ITS CONSTRUCTION AND USE

(A contribution from a research project sponsored by the Committee on Sedimentation of the National Research Council)

Fred M. Varney

A bottom-sampler for procuring cores several feet long has been developed recently. Designed for use on the 34-foot ketch Quequeg, this instrument had to be light, inexpensive, operated with ease by a three-man crew, effective in deep water under various conditions of wind and sea, and of a type that could be handled with a light winch and light cable. The sampler consists essentially of a light cylindrical core-barrel that is held upright on the sea-bottom by a float, and is driven into the mud by a stream-lined lead hammer, which slides along the core-barrel.

A folding tripod-support for the core tube was successful in an experimental model, but proved unwieldy when built to full size. If a vessel large enough to carry a cargo-boom were available, this difficulty would probably not be encountered. A float-support was considered

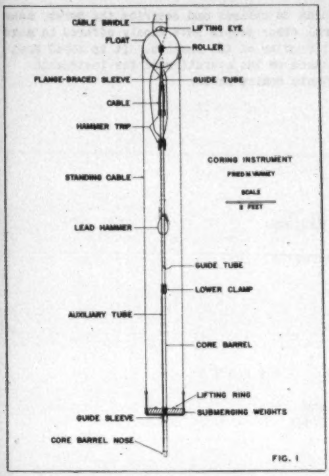

FIG. 1

as an alternative. It became evident that the core-tube should be independent of the float, and that the float should be held submerged by weights resting on the sea-bottom. A device of this type was built with a cylindrical float at the top of a long wooden frame weighted at the bottom, the frame serving as a track for guiding the core-tube. A hammer slid on the tube and was operated with the same cable that lowered the instrument to the sea-bottom. The instrument was modified during the course of ten offshore coring trips. In spite of makeshift construction, it took satisfactory cores five feet long in water 200 feet deep. It was not possible to core at greater depth because of the collapse of the float.

An instrument designed to take cores in water 3500 feet deep is now being constructed (see Fig. 1). The float, cast in an aluminum alloy, is an 18-inch sphere with a buoyancy of 65 pounds. Bosses on its sides are machined to receive both rollers for the running cables and shackles for the standing cables. A flange-braced sleeve cast integral with the bottom of the float, grips the end of a guide-tube on which the upper part of the core-barrel slides. The core-barrel is a steel tube 15 feet long and 1.5 inches in outside diameter. The hammer, tripped to fall free of the cable, has a stroke of 6.5 feet; it pounds against a clamp bolted around the core-barrel. The two submerging weights, half discs of iron, are connected with the float by standing cables. To ease the handling, the weights are lifted on and off while the instrument hangs alongside the boat in the water.

An important and effective feature of the instrument is the small-bore auxiliary tube, which eliminates suction during the core-barrel's withdrawal from the sediments. It is kept closed while the core-barrel is being driven into the sediments, but opens and lets water into the potential cavity below the barrel, as the barrel is drawn out. This device reduces greatly tension on the cable while the core-barrel is being withdrawn, and renders a catch or valve unnecessary for retaining any but very loose cores.

The cable for operating the instrument is 5/32-inch galvanized airplane strand. It is wound on a hand winch supplied with a quick-acting clutch and a brake of large area. For work at depths greater than 1000 feet, however, a motor-drive will be necessary. As the motion of the boat jerks the cable dangerously and interferes with the hammering action, the cable should be run over a sheave mounted on a spring-suspended boom. Alternate heaving in the cable by hand and suddenly slacking, has been the method of hammering. This has not been very satisfactory, and in the future, with the aid of the hammer-trip, the cable will be managed entirely on the winch.

The weight of the assembled instrument in air is 200 pounds; as handled on the boat's halyards without the submerging weights, it weighs 130 pounds; in water it weighs about 70 pounds. The total length is 17 feet. When the instrument is dismantled, all parts but the core-barrel can be stowed below deck.

The preliminary work was begun in September 1934 in collaboration with Kenneth L. Edwards, under the direction of Professor U. S. Grant of the Geology Department, University of California at Los Angeles. The work is being continued with Lowell Redwine of the same department, and with the help of a research grant to the writer from the Committee on Sedimentation of the National Research Council. Space does not permit acknowledgment here to all those who have contributed invaluable advice during the progress of the work. The writer, however, wishes especially to express his appreciation of the assistance and encouragement received from Dr. Parker D. Trask of the United States Geological Survey.

It is hoped that some of the conditions of sedimentation may be determined from examination of cores taken along a line crossing the Santa Monica Basin between Santa Monica and Santa Bar-

bara Island, California. Mr. Redwine and the writer plan to collect and describe the cores, make mechanical analyses, and interpret the results. Several other people have kindly offered to make foraminiferal, biological, chemical, and mineralogical studies of the samples. It is hoped that in another year more detailed information can be published on the operation of the instrument and on the nature of the subsurface sediments in the Santa Monica Basin.

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HORNBLENDITE AND RELATED ROCKS OF ANNETTE AND DUKE ISLANDS, SOUTHEASTERN ALASKA

A. H. Koschmann

(Published with the approval of the Director of the United States Geological Survey)

Annette and Duke Islands lie in the extreme southern part of southeastern Alaska just north of Dixon Entrance. They consist of crystalline rocks excepting a fringe of stratified rocks on the north, east, and south sides of Annette Island. The crystalline rocks consist of several varieties of gneiss, and igneous rocks which range from ultrabasic varieties to albite granite. The ultrabasic rocks consist of saxonite and hornblendite and are found chiefly on Duke Island. Intermediate rocks consist of gabbro and diorite. The core of Annette Island and the point on the northeast side of Duke Island consist of albite granite, the most silicic rock in the region. This paper deals chiefly with the hornblendite and associated hornblendic rocks and their origin. (For a more complete discussion of the geology of these islands the reader is referred to "The geology of Annette and Duke Islands, southeastern Alaska," to be published by the United States Geological Survey.)

General features

Distribution--The ultrabasic rocks form a broad central band through Duke Island conforming to the regional strike of north 35° west. This band is about 8 miles long and roughly 3 miles wide in the widest place. This large body contains some saxonite, an intergrowth of olivine and enstatite, but the larger part is hornblendite. The term hornblendite is used in this paper to denote a rock consisting essentially of hornblende irrespective of the less important associated minerals. A number of smaller bodies of hornblendite are distributed irregularly across the north end of Duke Island. Narrow dikes of very fine-grained hornblendite cut the coarse rock. Small lenses and irregular bodies also occur on Point Davison on the southwest end of Annette Island and cummingtonite dikelets cut the saxonite (Fig. 1).

Petrography--The outstanding feature of the hornblendite is its abrupt and extreme variation in texture and composition. It varies from a coarse granitoid rock with grains about one-quarter inch in diameter to a pegmatitic facies with crystals up to 4 feet (Fig. 2) or more in length, but rock with crystals from 1 to 6 inches long predominates. The coarse texture of hornblendite is apparently a universal feature noted by many observers. Clapp (C. H. Clapp, Geology of the Victoria and Saanich map-areas, Vancouver Island, B. C., Can. Geol. Surv. Mem., 36 pp. 68-69, 1913) has described hornblendite with crystals 2 to 3 feet long, Anderson (Alfred L. Anderson, An occurrence of giant hornblendite, J. Geol., v. 41, pp. 89-98, 1933) has described similar rock in Idaho with crystals as much as 14 inches in length, and crystals 6 inches long occur in hornblendite near Haines in southeastern Alaska (Adolph Knopf, The occurrence of iron ore near Haines, southeastern Alaska, U. S. Geol. Surv. Bull. 442, p. 145, 1910).

Banded or layered structures are common features of the hornblendite. On the south end of Duke Island just north of Kelp Island a layer of coarse hornblendite 6 to 8 feet thick is overlain by medium to coarse granitoid hornblendite, which in turn is overlain by a coarse facies with crystals 2 to 4 inches long. Similar extreme variations in texture have also been noted by Knopf (Adolph Knopf, Geology of the Berners Bay Region, Alaska, U. S. Geol. Surv. Bull. 446, pp. 25-26, 1911) in the Berners Bay area and by Buddington and Chapin (A. F. Buddington and T. Chapin, Geology and mineral deposits of southeastern Alaska, U. S. Geol. Surv. Bull. 800, pp. 194-198, 1929) in other parts of southeastern Alaska.

The composition of the hornblendite is also extremely variable. The coarse hornblendite on Duke Island apparently consists chiefly of green hornblende with only a minor amount of epidote which fills the interstices between the irregular hornblende prisms. The finer grained non-feldspathic facies consist of green hornblende and variable amounts of augite. Magnetite is the common accessory mineral, and biotite and epidote may or may not be present. The augite occurs as corroded remnants in the hornblende, but in some places it occurs as irregular grains with irregular blebs of hornblende which indicate replacement of the augite. Schiller structure is a feature of both the augite and hornblende. Still another variety of the black granitoid and extremely heavy rock occurring with typical hornblendite consists of cummingtonite, augite, accessory magnetite, and scattered grains of a green isotropic mineral, probably pleonaste, which is mostly enclosed in large magnetite grains.

Feldspathic varieties of the hornblendite are of two principal kinds: (1) Normal granitoid facies and (2) pegmatites. The granitoid facies occurs chiefly on the northeast side of Duke Island. The hornblende is the green variety and the feldspar varies from bytownite to oligoclase-

FIG. 1—DIKELETS OF CUMMINGTONITE IN SAXONITE; NOTE SHARP CONTACTS OF DIKELETS IN ENSTATITE PHENOCRYSTS (SCALE IN INCHES)

FIG. 2—LARGE HORNBLENDE CRYSTALS ON NORTH END OF DUKE ISLAND OPPOSITE VEGAS ISLAND; INDIVIDUAL CRYSTALS, SOME TWO FEET LONG, OUTLINED BY REFLECTION FROM CLEAVAGE SURFACE (PHOTOGRAPH BY H.C. COOMBS)

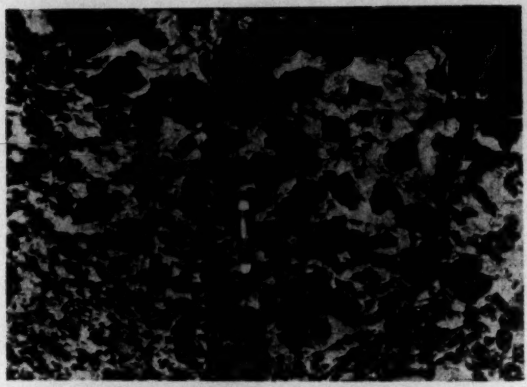

FIG. 3—HORNBLENDE-PLAGIOCLASE PEGMATITE ON SOUTH SLOPE OF DUKE ISLAND (PHOTOGRAPH BY H.C. COOMBS)

FIG. 4—BANDED HORNBLENDE-PLAGIOCLASE PEGMATITE ON SOUTH SIDE OF DUKE ISLAND

FIG. 5—BANDED HORNBLENDE-PLAGIOCLASE PEGMATITE CONTAINING HORNBLENDE AUGEN ON SOUTH SIDE OF DUKE ISLAND (PHOTOGRAPH BY H. C. COOMBS)

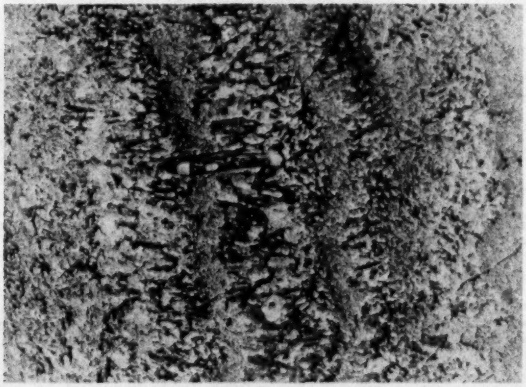

FIG. 6—COMB STRUCTURE IN HORNBLENDE-PLAGIOCLASE PEGMATITE ON SOUTHWEST SIDE OF DUKE ISLAND (PHOTOGRAPH BY H. C. COOMBS)

andesine. In the more hornblendic facies corroded plagioclase grains occur in the hornblende. With increase of plagioclase this facies grades into hornblende gabbro. Accessory minerals are biotite, magnetite, and in one section garnet.

The hornblende pegmatites are extremely abundant. Their extent and form is not extensively revealed but they appear as an irregular border at the margin of the hornblendite. They consist chiefly of an irregular intergrowth of hornblende and feldspar (Fig. 3) but hornblende usually predominates. Some are banded (Fig. 4) and the hornblende crystals appear as augen (Fig. 5). Still others have a comb structure in the bands (Fig. 6). The hornblende pegmatites consist chiefly of calcic plagioclase, ranging from bytownite-anorthite to anorthite (An_{98}), and green hornblende. Accessory minerals are epidote, zoisite, biotite, muscovite, chlorite, magnetite, pyrite, apatite, and a zeolitic mineral. Epidote and zoisite may form almost 50 per cent of the rock. Veinlets of plagioclase cut hornblendite and are clearly later, but pseudo-cataclastic texture is common in the typical plagioclase-hornblende pegmatites and plagioclase in part has been replaced by hornblende and the accessory minerals.

Hornblende in varying amounts is also a prominent constituent of many of the other igneous rocks of the region. In most of them it occurs as metacrysts. It is especially abundant in the gneiss and in the igneous rocks on the west side of Annette Island. Some of these rocks have been so extensively hornblendized that they vary greatly from place to place and their original character is largely obscured. Large unbroken hornblende metacrysts occur as augen in some rocks with cataclastic structure. Biotite, apatite, and small amounts of titanite and zircon are associated with the hornblende. Hornblende also occurs in places in the albite granite which consists of albite and quartz and variable amounts of microperthite. The albite varies from Ab_{90} to Ab_{95}. Dark minerals are absent from the typical albite granite, but in the northern part of the granite-body hornblende occurs as euhedral crystals. The hornblende is the normal green variety and not one of the sodic amphiboles such as hastingsite, riebeckite, or arfvedsonite which might be expected in a sodic granite.

Origin

Hornblende occurs as large relatively pure bodies, as dikelets, in feldspathic rocks which grade into hornblende gabbro, in pegmatites, and disseminated in the country rock in such a way so as to indicate replacement or hornblendization. In considering the origin of the hornblendite it will also be necessary to find a theory sufficiently inclusive to explain the regional hornblendization, for in view of the fact that all these varieties of rocks occur within a small area the hornblende is believed to have a common genetic history.

The widespread hornblendization of the country rock is undoubtedly to be explained by metasomatic processes but it is doubtful whether the large mass of hornblendite can thus be accounted for. In most of the fine-grained black hornblendite on Duke Island corroded remnants of pyroxene are prominent and pyroxene can hardly be regarded as having been deposited by the same hydrothermal solutions which deposited the hornblende. Pyroxenes and also olivine have been described as common minerals in hornblendites the world over. Williams (G. H. Williams, The peridotites of the "Cortlandt Series" on the Hudson River near Peekskill, N. Y., Amer. J. Sci., v. 31, pp. 29-37, 1886) found both olivine and hypersthene in the "Cortlandt Series" and states that "next to hornblende olivine is the most important mineral which is remarkable both for its freshness and its beautiful inclusions." Near Haines, southeastern Alaska, according to Knopf (A. Knopf, op. cit., p. 145) the hornblendite contains more or less admixed augite; Cohen (E. Cohen, Berichtigung bezüglich des "Olivine-diallage Gesteins" von Schriesheim im Odenwald, Neues, Jahrb. Min., v. 1, p. 242, 1885) describes olivine as the chief associated mineral in the Schriesheim rock and Thompson (J. A. Thompson, The hornblendic rocks of Glendalough and Greystones, Q. J. Geol. Soc., v. 64, pp. 477-480, 493, 1908) found remnants and pseudomorphs of olivine in the Glendalough rocks.

The metasomatic theory regarding the origin of hornblendites as a whole is also opposed by the occurrence of some hornblendites as sills and dikes. The mode of occurrence of the large mass of hornblendite on Duke Island is uncertain, but its distribution parallel to the regional structure suggests that it is a sill-like mass. Buddington and Chapin have pointed out that hornblendites in southeastern Alaska are "repeatedly found as sills and southeast of Petersburg, on Mitkof Island, intrusive masses of hornblendite have produced contact metamorphism in the adjoining slates, with the formation of such minerals as andalusite" (A. F. Buddington and T. Chapin, Geology and mineral deposits of southeastern Alaska, U. S. Geol. Surv. Bull. 800, pp. 248-249, 1929).

Hornblendites and amphibolites also occur as dikes. Dikes of cummingtonite cutting the saxonite are found on Duke Island and Spurr (J. E. Spurr, Geology of the Yukon Gold District, Alaska, U. S. Geol. Surv., 18th Annual Report, pt. 3, pp. 227-228, 1898) has described dikes up to 20 feet in thickness consisting of green hornblende, epidote, and pyrite, pyrrhotite, and ilmenite, and others of large crystals of hornblende, pyroxenite, and mica, "intergrown in pegmatitic fashion." He states further (idem, p. 232) that the "most basic dikes are composed sometimes entirely of hornblende, sometimes of pyroxenite, and sometimes of both intermingled," and in places grade into feldspathic rocks. Also Adams and Barlow (Frank D. Adams and Alfred E. Barlow, Geology of the Haliburton and Bancroft areas, Ontario, Can. Geol. Surv., Mem. 6, pp. 159-160, 1910) have described "amphibolite" dikes cutting limestone. Most students regard hornblendite to have been derived from peridotites and allied rocks. The occurrence of corroded grains of pyroxenes in the poikilitic hornblende and the repeated association of hornblendites with peridotites and the gradation of one into the other strongly indicate a direct relationship with the ultrabasic rocks. Williams (G. H. Williams, The gabbros and diorites of the "Cortlandt Series" on the Hudson River near Peekskill, N. Y., Amer. J. Sci., v. 35, pp. 438-448, 1888) in discussing the origin of the brown hornblende in the hornblendite of the Cortlandt series of ultrabasic rocks states that "the brown hornblende from both the diallage and hypersthene is so

apparent as to suggest the derivation of all the hornblendites by paramorphism from preexistent pyroxenites." Wyllie and Scott (B. K. N. Wyllie and A. Scott, The plutonics of Garabal Hill, Geol. Mag., v. 10, pp. 500-505, 1913) have described similar rock composed of brown hornblende and cores of diallage, which they called "davainite" and distinguish from hornblendite regarded by them as end-member of the diorite series and conclude that "all the hornblende was formerly pyroxene." A similar view has also been expressed by Rosenbusch (H. Rosenbusch, Mikroscopische Physiographie der Mineralien und Gesteine, 4th ed., v. 2, pt. 1, p. 483, 1907).

Although the secondary character of hornblendite after a preexistent ultrabasic rock is generally recognized, few authors discuss the cause or process of alteration. Thompson (J. A. Thompson, op. cit., p. 478), after a thorough study of the hornblende peridotite in the Glendalough and Greystones district, concluded that "their relations are suggestive of magmatic resorption of the augite with formation of hornblende." Wyllie and Scott (Wyllie and Scott, op. cit., p. 502) concluded that the conversion of diallage to hornblende may have occurred (1) "during cooling and may denote a transition-temperature below which hornblende is stable, and above, diallage, (2) the change may be due to some kind of annealing of the diallage rocks by the later diorite magma, which, as we have noted, is in intimate contact with the davainite." These authors favor the "annealing" theory.

The occurrence of hornblendite in sills and dikes, referred to above, hardly permits a simple hydrothermal alteration of a preexistent peridotite. Such a theory would require that after the emplacement and crystallization of the peridotite immense volumes of heated solutions, probably originating in the deep-seated magma chamber, follow the identical channels originally followed by the peridotite magma. The evidence at hand is more suggestive that the hornblendite was derived from a magma in which the hydroxyl and fluorine required by the hornblende were inherent constituents. Buddington and Chapin (A. E. Buddington and T. Chapin, op. cit., p. 249) have pointed out that apatite up to 4 per cent is a common constituent of hornblendites in southeastern Alaska, and the coarse crystallization of the hornblendite together with other accessory minerals as biotite, titanite, and zircon suggest that mineralizers were an important constituent of the magma. To account for coarse hornblendite in Idaho, Anderson (Alfred L. Anderson, An occurrence of giant hornblendite, J. Geol., v. 41, p. 96, 1933) has postulated that the rock was crystallized from a magma "rich in volatile or aqueous matter and of more or less pegmatitic character."

The presence of corroded olivine and pyroxene indicate that the first minerals to crystallize were olivine and pyroxenes and crystallization apparently followed Bowen's (N. L. Bowen, The evolution of the igneous rocks, Princeton Univ. Press, pp. 54-62, 1928) reaction-series. The absence of olivine in some hornblendites indicates it may not have formed; on the other hand, olivine, subsequent to its crystallization, may have been completely resorbed or replaced. As crystallization progressed and as the magma became enriched in the volatile constituents, especially water, and the magma slowly cooled, it finally became saturated with hornblende which then began to crystallize. At this time the early precipitated olivine and pyroxene were no longer in equilibrium with the liquid phase and were reacted upon and replaced by hornblende. That equilibrium was not completely established is attested by the corroded cores of olivine and pyroxene included in hornblende.

It is not improbable that the granitoid even-grained hornblendite and cummingtonite masses represent replacement of peridotite, whereas the coarse hornblendite may represent direct precipitation from the aqueous magma. The mineral cummingtonite is also present in the associated saxonite, and this relationship at least suggests that it is somewhat earlier than hornblende and probably formed at a higher temperature and at a stage when the magma was less hydrous than the stage of hornblende development. This stage was followed by the development of the hornblende-plagioclase pegmatites. This in turn was followed by the hydrothermal stage, and the residual solution at this stage migrated widely and permeated the country rock and produced hornblendization on a grand scale.

The hydrothermal solutions undoubtedly also were able to alter the preexistent mafic minerals in the country rock. On the northeast end of Duke Island feldspathic hornblendite grades into gabbro by decrease in hornblende and the appearance and relative increase in pyroxene and olivine. Buddington and Chapin (A. F. Buddington and T. Chapin, op. cit., p. 249) have shown that feldspathic hornblendites "are of such a composition that if calculated in terms of anhydrous minerals they may be shown to be equivalent to an olivine gabbro," and believe "that the hornblendites may have resulted from the crystallization of a magma of a composition which would usually have produced an olivine gabbro, but which in the presence of a relatively high content of volatile materials, particularly water, formed hornblendite." However, the field-relations on Duke Island indicate that the feldspathic hornblendite and the associated hornblende gabbro represent an altered and hornblendized gabbro produced by the escaping hydrothermal solutions of the ultrabasic magma.

Summary

The large mass of hornblendite on Duke Island is believed to have formed by primary crystallization of pyroxenes from an ultrabasic magma high in volatile constituents and subsequent conversion into hornblende. In the early stages of crystallization pyroxenes were precipitated but ultimately the magma became saturated with hornblende which then began to crystallize. The early formed pyroxenes were in part replaced but in part remain as corroded inclusions in the hornblende. The cummingtonite masses and dikes which also contain corroded pyroxene very probably represent resorption of Mg-Fe pyroxene and possibly olivine. The end-phase of crystallization from the residual magma is represented by the marginal pegmatites. The granitoid feldspathic hornblendite which is commonly associated with gabbro is very probably hydrothermally altered gabbro and hydrothermal solutions also migrated widely and effected hornblendization of the country rock on a large scale.

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THE SIERRA NEVADA PLUTON, CALIFORNIA

Ernst Cloos

(Abstract)

The term "batholith" is avoided, because as originally coined it does not fit the Sierra Nevada igneous complex, and as newly defined it may lead to confusion.

The Sierra Nevada Pluton is composed of an innumerable amount of smaller intrusives, each with its individual structure and following each other at close intervals. Structure studies show that the intrusions progress from west to east and that similar rock types appear at the same time along the entire pluton. The units grow steadily by addition of newer ones and the consolidation of the older ones. In the last stage, the present pluton is jointed as a whole and uplifted.

The pluton as a whole plunges northward. It is exposed at lower levels in the south and at higher levels in the northern portions. The development of Mother Lode structures and their mineralization is parallel to this development, being richer in the north than in the southern portion. The form and structure of part-plutons differ in the northern portions from central or southern sections. Contacts in the Yosemite section partly are inclined towards the pluton.

The emplacement of the pluton required a long time because older part-plutons were consolidated before the following magmas were intruded, and this process was repeated at least eight times. The magma of each part-intrusion seems identical along the strike of the entire pluton. It therefore must have come from great depths and the narrow, almost dike-like opening must also have reached greater depths.

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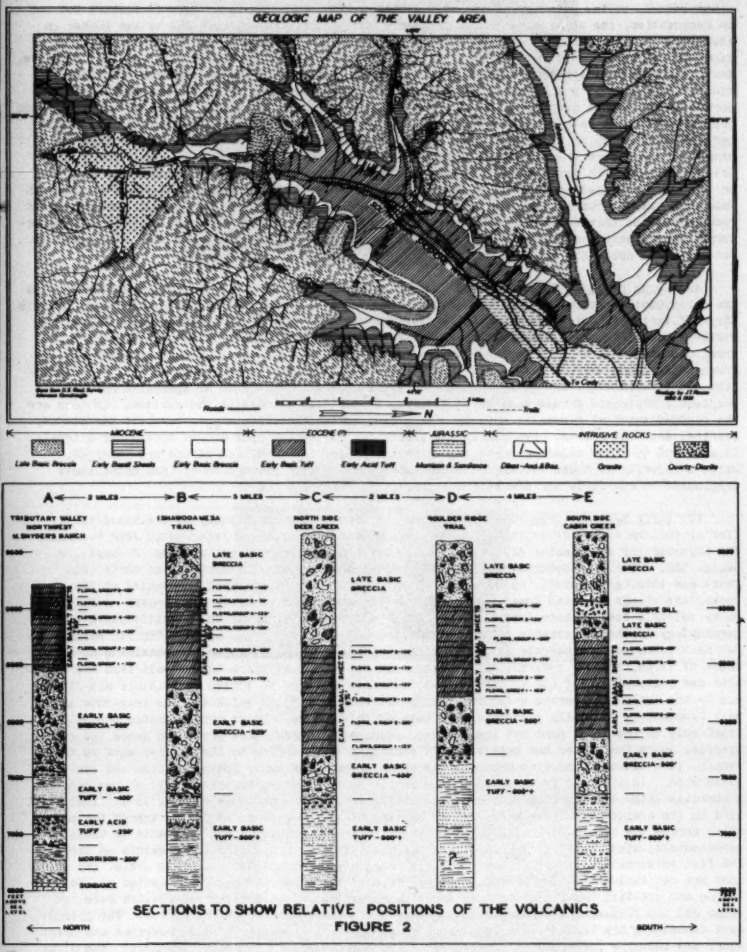
THE VOLCANIC ROCKS OF THE VALLEY AREA, PARK COUNTY , WYOMING

John T. Rouse

(I) Introduction

It is the purpose of this paper to give a detailed description together with a discussion of the mode of origin of a series of the Absaroka volcanic rocks. The area lies within the limits of the Ishawooa Sheet of the Absaroka Folio (No. 52) and the Valley Post Office, near the center of the region, is on the South Fork of the Shoshone River, about 43 miles southwest of Cody, Wyoming. The Ishawooa Sheet was originally mapped under the direction of Arnold Hague in 1893 and 1897 and the subdivisions of the volcanics which the writer used in mapping this region are essentially the same as those used by Hague and others throughout the Absaroka Mountains and Yellowstone National Park. These subdivisions are shown in the legend of the geologic map, Figure 1. The plan of this paper is to give first a description of the pyroclastic rocks together with a discussion of their mode of origin and to follow this with a similar treatment of the early basalt sheets.



SECTIONS TO SHOW RELATIVE POSITIONS OF THE VOLCANICS
FIGURE 2

(II) Pyroclastic rocks

(A) Early acid tuffs--Only one exposure of the early acid tuffs was found. It outcrops in a narrow band, 250 feet thick, on the west side of the South Fork Valley about 2 miles above Ishawooa Creek (Fig. 1). The base of the tuff shows tuffaceous, conglomeratic beds a few feet thick in which white, vesicular pebbles of dacite about one-half inch in diameter are imbedded in a light-colored volcanic ash. Intercalated with these conglomeratic beds are thin, light-gray to greenish-gray beds of exceedingly fine-grained, delicately laminated, and in most cases

cross-bedded, tuffs. The top of the acid series differs from the lower part in texture but not in composition, the upper zone having fragments and pebbles varying from one to two inches in diameter. Mineralogically these acid tuffs agree very well with the same tuffs described by Hague and others in adjacent regions--that is, composed of hornblende-andesite, dacite, andesite, and occasional rhyolite and basalt fragments. The ground-mass is so exceedingly fine that little could be done in a microscopic determination of the minerals, but some free quartz was observed in the almost completely isotropic matrix. The extreme hardness of some of the finer beds suggests that they have undergone some silicification. No calcite was observed in this matrix and the application of hydrochloric acid to a fresh face gives a reaction so minute under a binocular microscope that it can be regarded as negligible. Unlike the early acid tuffs and breccias observed in other regions, these do not show any xenoliths of older schists, gneisses, or limestone, carried up from below (John T. Rouse, Genesis and structural relations of Absaroka volcanics, Amer. Mineralogist, v. 20, p. 206, 1935). The acid tuffs in this area probably never reached a great thickness and this, together with the well-known fact that widespread erosion occurred after their accumulation and before the eruption of the later basic tuffs, would account for the small areal distribution.

(B) Early basic tuffs--Because of the two distinct units in the series originally mapped as the early basic breccia, it has been divided into a lower, basic tuff and an upper, basic breccia. The tuff varies in thickness from 400 feet at the northern part of the area to 900± feet at the southern part (Fig. 2). The greater part of these tuffs were water laid as is evidenced by cross-bedding, intercalated beds of conglomerates several inches thick, and the presence of fresh-water unios and one fresh-water gastropod. These tuffs are remarkably similar in composition and texture over wide areas. Under the microscope the tuffs show an aphanitic and almost completely isotropic ground-mass which makes up 50 per cent or more of the section. In this are the rounded euhedral minerals; andesine ($Ab_{55}An_{45}$), oligoclase ($Ab_{75}An_{25}$), basaltic hornblende, biotite, and some quartz. Frequently the pieces of biotite are bent around some other minerals. In addition to these major minerals, occasional apatite, titanite, and zircon are observed. While a majority of these tuffs were water-laid, still a fair proportion of them doubtlessly originated as ash falls and are lithic tuffs.

(C) Early basic breccia--The early basic breccias rest unconformably on the basic tuffs (for an outline of the geologic history of this region the reader is referred to John T. Rouse, The physiography and glacial geology of the Valley Region, Park County, Wyoming, J. Geol., v. 42, p. 740, 1934). In contrast to the tuffs, these breccias are thickest at the north (900 feet) and thin, going south, to 500 feet. Because of the great contrast in texture of the rocks, the change from the lower basic tuffs to these breccias is quite pronounced. A band of heavy volcanic conglomerate (see C. K. Wentworth and Howell Williams, The classification and terminology of the pyroclastic rocks, Nation. Res. Council, Bull. 89, p. 50, 1932, in which they define a volcanic conglomerate as "sedimentary, coarse pyroclastic material containing an abundance of large, chiefly rounded, water-worn fragments. In most cases they result from the erosion and redeposition of old volcanic rocks, but they may also be formed by volcanic mud-flows and by the action of running water on freshly fallen ejecta.") in which all the fragments are well rounded, is generally present at the base of this series. These conglomerates are not confined only to the basal zone but are, rather, present throughout this group and hence the name breccia, which the writer has kept to avoid confusion in referring to the earlier work in this region, is a misnomer and this group should be referred to as early basic breccias and conglomerates. In all, the group represents a series of alternating breccias (Fig. 3) and conglomerates (Fig. 4), together with some thin tuffaceous beds. Definite bedding is difficult to find in the breccias, but the well-defined bedding of the conglomerates can be traced for many miles across the area. It is difficult to state the average size of the fragments in these pyroclastics, since these vary from pieces the size of ordinary pebbles to fragments as large as 175 feet in diameter. These abnormally large fragments are confined to certain areas, and if they are not included in the average then the size of the fragments can be estimated as one foot to one and one-half feet in diameter. Exceptional variations in mineral composition were not found and the following mineralogical description is applicable to all the series. The ground-mass containing the large fragments, comprises 40 to 50 per cent of the conglomerates and breccias, and contains the following (named in order of abundance): Andesine ($Ab_{60}An_{40}$), and oligoclase ($Ab_{75}An_{25}$) as clear lath-shaped crystals; euhedral and rounded diopside; magnetite; idiomorphic crystals of common hornblende; and some chlorite. The isotropic matrix (65 per cent) which contains the above minerals is mainly dark gray to brown, the constituents of which could not be determined with the microscope. Part of the ground-mass of some of the flow breccias is crystalline, mainly andesine, and the remainder is a dark, nearly black, glass.

The most abundant fragments in the ground-mass are pyroxene-andesites very rich in andesine ($Ab_{65}An_{35}$) together with diopside, chlorite, orthoclase, magnetite, and some apatite. In addi-

FIG. 3—VOLCANIC BRECCIA ON THE SECOND NORTHERN TRIBUTARY OF DEER CREEK

FIG. 4—VOLCANIC CONGLOMERATE ON THE WEST SIDE OF THE SOUTH FORK RIVER, NEAR VALLEY RANCH

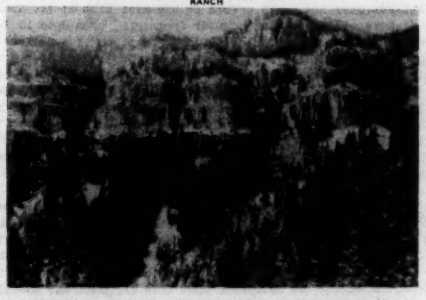


FIG. 5—EARLY BASALT SHEETS ON DEER CREEK; NOTE THE SEPARATE AND DISTINCT CLIFFS BY EACH GROUP OF THE LAVA-FLOWS OF THIS SERIES

tion, fragments of hornblende-andesites are common, but only a very few fragments of basalts were found.

From the foregoing description it is evident that these pyroclastics are andesitic breccias and conglomerates.

At many outcrops of the breccias and conglomerates a bright dark-green stain was observed which might easily be confused with a copper stain. It is a green chalcedony coating the fragments and staining the matrix. The writer is indebted to Professor A. H. Phillips who made a qualitative analysis of this chalcedony and found no trace of copper but considerable ferrous iron and manganese, the presence of which would account for the green color of this chalcedony.

(D) Late basic breccia--This series is separated from the early basic breccia by 750 to 975 feet of lava-flows which will be described later. In this area no exposures of the late acid breccia were found. A description of the late basic breccia would be a duplication of that just given for the early basic breccia and Hague has stated "---- in some instances where the basaltic sheets themselves are wanting the two breccias apparently come together rendering it impossible to distinguish between them" (Arnold Hague, Absaroka Folio, No. 52, p. 4, 1898). It would suffice, therefore, to state that this breccia, varying from 2000 to 2500 feet in thickness, is composed of breccias, conglomerates, agglomerates, and some thin beds of tuffs; that the fragments are more regular in size (average one to two feet); and no unusually large fragments, such as those in the early basic breccia, were found.

(III) Origin of the pyroclastics

The following discussion concerns the early pyroclastics. In the early descriptions of this region and adjacent areas the writers gave no mention of the mode of origin of the breccias, tuffs, and conglomerates other than a statement that these ejectementa had been thrown from many vents scattered over the area and that the vents are now, for the most part, obliterated by the successive piling up of later material. Detailed studies have shown that many agencies were responsible for the accumulation of these pyroclastics and the present structures and textures are dependent on many processes at work at the time of volcanic activity.

The origin of the acid and basic tuffs presents no unusual problem as they represent either volcanic dust-falls or, for the greater part, water-laid equivalents of these dust-falls. On the other hand, the problems connected with the coarse pyroclastics are numerous and puzzling. The great number of conglomerate beds, composed of perfectly rounded fragments, would necessitate stream-action as an important factor of deposition of much of the early basic breccia series. This rounding, together with the deposition of heavy conglomerate beds 10 to 50 feet thick, requires a lengthening of the period of accumulation of this early series and would indicate that accumulation was not a sudden, rapid explosive process. This hypothesis is further substantiated by the series of buried forests in the early basic breccia in Yellowstone National Park (F. H. Knowlton, Fossil flora (Yellowstone National Park), U. S. Geol. Surv., Mon. 32, pt. 2, pp. 755-761, 1899).

The fact that mud-flows were an active agent during this volcanic period is illustrated in the vertical cliffs between Deer and Cabin creeks on the west side of the South Fork. Exposures show a heterogeneous mixture of rounded and angular fragments, some 6 to 10 feet in diameter, held together by a tuffaceous cement. Blackwelder's description of mud-flows (Eliot Blackwelder, Mud-flows as a geologic agent in Semiarid Mountains, Bull. Geol. Soc. Amer., v. 39, pp. 465-480, 1928) would adequately describe these exposures. During accumulation, some of the breccias, thrown out on rather steep slopes, sought lower elevations by flowing down these slopes as mud-flows. This conclusion is strengthened after observing that this particular mud-flow, like others, is located on the side of a valley, cut into the earlier tuffs prior to the accumulation of the breccias. This is reasonable since there are no large volcanoes here, on whose slopes mud flowage might take place, and it is therefore necessary to look to the steeper slopes of the pre-breccia topography which would, in a large measure, control these flows.

The size of the fragments in the breccia would indicate great volcanic explosions of an unusual type. Some large fragments are found in the explosive breccias where mud-flows cannot be called on to explain their present position in the breccias. The largest of these fragments in this area, unfortunately inaccessible because its cross-section shows in the middle of a vertical cliff 500 feet high, was estimated to be 175 by 50 feet in visible section. This illustrates the tremendous forces accompanying the outbursts when this fragment was doubtlessly blown from a nearby vent. Bucher has used this fragment to illustrate "unmistakable evidence pointing to volcanic explosions far greater than those recorded by man" (W. H. Bucher, Volcanic explosions and overthrusts, Trans. Amer. Geophys. Union, 14th Annual Meeting, p. 241, 1933).

The presence of a partly crystalline ground-mass, containing plagioclase and glass, in some of the breccias is proof that the ground-mass of these was molten at the time of extrusion and probably remained in a similar state until these breccias came to rest in their present position.

The pyroclastic rocks of this region are then classified according to origin as: (1) Water-laid tuffs and conglomerates; (2) explosive breccias; (3) flow breccias; and (4) mud-flows.

Positive proof of the existence of one of the vents in the neighborhood of Ishawooa Mesa, between Deer and Ishawooa creeks, is not to be had but the fact that the breccia is thickest in this vicinity is suggestive. The breccias thin to the south (see Fig. 2) and while the thickening of the tuffs in this direction might not harmonize with some ideas regarding maximum thickness of beds near the vents, still it must be remembered that certain factors enter into the distribution of the tuffs which do not necessarily apply to the breccias. Anderson (Charles A. Anderson, The Tuscan formation of northern California, Univ. Cal., Pub. Dept. Geol. Sci., v. 23, No. 7, pp. 215-276, 1933) has pointed out that the coarser erupted material will fall near the vent and hence be thicker there, while the distribution of the finer material is influenced by the wind. In the Valley Area streams depositing the tuffs would also be an important factor. This greatest thickness of the breccia, together with the heterogeneous assortment of large fragments, would suggest the presence of a local vent nearby. These are two features associated with known vents, where other factors are to be had definitely proving their existence, that the author has found in other localities in the Absaroka Mountains.

(IV) Early basalt sheets

These lava-flows were erupted from many fissures throughout the area as is evidenced by their relatively uniform thickness over wide areas and absence of dip away from any common center.

(A) Petrography--The early basalt sheets, resting unconformably on the early basic breccias, 50 to 975 feet thick, are made up of many flows varying from 50 to 125 feet in thickness. Practically all of the flows are porphyritic basalts most of which show good columnar jointing, a feature of considerable value in interpreting the presence of an unconformity between these and the underlying breccias. Good exposures of these basalts show that they make a series of five or six vertical cliffs on valley sides (Fig. 5) and on the basis of stratigraphic position and petrographic character, these basalt sheets have been divided into six groups. In the petrographic descriptions which follow, the reader is referred to Tables 1 and 2, modes and chemical analyses of the different groups. Unless otherwise stated, each group assumes a constant mineralogical composition throughout the area.

Table 1--Average modes of each group of the lava-flows
(Numbers at the top of the columns refer to subdivisions in the text)

Group	1A	1	2	3	4	5	6
Labradorite	30.2		26.9		20.0	23.2	
Andesine-Labradorite		30.6		25.7			19.2
Orthoclase	11.3						
Olivine	27.4		1.3	5.0			
Augite	19.7	19.1	6.7	8.0	8.0	20.1	4.1
Leucite	3.6						
Ground-mass	7.8[a]	50.3[b]	65.1[c]	61.3[d]	72.0[e]	56.7[f]	76.7[g]

[a] Includes magnetite 5 per cent, apatite 1.8 per cent, and glass 1 per cent.
[b] Crystalline--includes small crystals of labradorite, orthoclase, augite, magnetite, apatite.
[c] Mostly labradorite with some iddingsite, magnetite, glass, and chlorite.
[d] Plagioclase, glass, magnetite, and apatite.
[e] Mainly glass.
[f] Dark glass, plagioclase, magnetite, and apatite.
[g] Mainly plagioclase and glass with some magnetite.

Group 1--The basal flows are generally very coarse grained and show more variations in composition and texture than do the flows of any of the other groups. They are, however, all similar in that they carry an appreciable amount of either pyroxene and/or olivine as large phenocrysts in a ground-mass made up almost entirely of small lath-shaped plagioclase crystals together with light greenish-brown glass. Because of the coarse texture of some of these lava-flows and the high percentage of the ferromagnesian phenocrysts, they weather very easily and do not produce vertical cliffs. At the northeast end of the area, the basal flows show a striking similarity to the type of rock Iddings described as absarokite (J. P. Iddings, Absarokite-Shoshonite-Banakite

Series, J. Geol., v. 3, pp. 935-959, 1895). In thin section the flow shows rounded crystals of olivine; augite; feldspar, both orthoclase and labradorite ($Ab_{45}An_{55}$) as lath-shaped crystals in the ground-mass; leucite entirely as anhedral grains; apatite in exceedingly long needles (0.75 to 1.25 mm); minor constituents which include magnetite, iddingsite, chlorite, and a dark glassy ground-mass. On the basis of this mineral composition together with the chemical analysis (see section on petrology), this rock has been designated as labradorite-leucite-absarokite.

The basal flows of the southern part of the area are quite different in composition and appearance from that just described. Thin sections of this basalt show andesine-labradorite ($Ab_{50}An_{50}$) and augite as phenocrysts in a crystalline ground-mass composed of laths of plagioclase and nearly equidimensional grains of orthoclase together with some small crystals of apatite, magnetite, and pyroxene. These flows are augite basalts.

Group 2--These basalts are characteristically quite dense having, in the hand specimen, only a few recognizable minerals of pyroxene and plagioclase. Microscopically the ground-mass of this basalt is practically all small plagioclase crystals in which are imbedded phenocrysts of labradorite ($Ab_{45}An_{55}$), augite and small rounded crystals of olivine. Other constituents of the ground-mass include iddingsite, magnetite, chlorite, and glass.

At the top of this group a thin (3 to 6 feet) bed of bright red, fine-grained tuff is found throughout the entire area to which Hague (Arnold Hague, op. cit., p. 4, "Not infrequently they--the early basalt sheets--carry interbedded thin layers of silt and fine breccias, and in places show evidences of atmospheric agencies acting upon surface flows before the pouring out of fresh lavas") has previously referred. Evidence that this represents a baked tuff follows. The thin sections show some shards of clear glass in lune and sickle-shaped forms in a fine-grained isotropic ground-mass. Large, clear unweathered fragments of plagioclase and augite were observed which would indicate that this was a tuff rather than the upper part of the flow reddened by atmospheric agencies.

Group 3--Microscopically the augite-basalts of this group are very similar to those of Group 2 having a dark, dense ground-mass in which phenocrysts of pyroxene and plagioclase are contained, but in Group 3 the flows seem to be more abundant in pyroxene and the ground-mass contains an appreciable percentage of small white zeolites, phillipsite. In thin section the phenocrysts of augite are clearer and more completely idiomorphic than are the phenocrysts of andesine-labradorite ($Ab_{50}An_{50}$), the latter being invariably fractured and frequently altered along the cleavage planes. Olivine is also present as a phenocryst and associated with it is iddingsite. The ground-mass, except for a few glassy phases, is mainly plagioclase, together with some magnetite grains and a few apatite needles.

Group 4--These basalts are lighter colored and less porphyritic than any previously described. In the main they are dark gray and a few phenocrysts of plagioclase and pyroxene, the former being more abundant, are visible in the hand specimen. Many of the flows of this group are amygdaloidal, the amydules generally being filled with white calcite. In thin section these show a very fine, completely crystalline ground-mass composed of plagioclase, pyroxene, magnetite, apatite, and some chlorite in which are contained the following phenocrysts: Clear beautifully twinned labradorite ($Ab_{45}An_{55}$); and equally clear, light-green augite. No olivine was found in this group.

Group 5--Over the greater part of the area the flows of this group are black pyroxene basalts, the hand specimens showing a large amount of plagioclase and pyroxene phenocrysts together with some iddingsite. The regularity of this type of flow is broken by occasional exposures where the basalt is lighter in color and augite as a phenocryst is lacking. In these lighter flows, which are rare, plagioclase is the only abundant phenocryst, but there are also a few red crystals of iddingsite visible in the hand specimen.

Microscopically the lighter colored flows of this group show a ground-mass of delicate, lath-shaped crystals of labradorite, a considerable proportion of glass, some leucite in allotriomorphic grains, very small pyroxene crystals, magnetite and apatite. The phenocrysts, with the exception of iddingsite, are all clear, well-twinned labradorite ($Ab_{45}An_{55}$); the plagioclase is badly fractured and the borders of the crystals show signs of resorption. The iddingsite occurs as scattered, bright red patches throughout the ground-mass.

The thin sections of the more common dark pyroxene-basalt show labradorite ($Ab_{40}An_{60}$) and augite as the predominant phenocrysts in a ground-mass that is, when compared to the ground-mass of flows of the other groups, rather coarse and composed of glass (large per cent), plagioclase, magnetite, apatite, and iddingsite.

Group 6--This last group of flows is a dense, black basalt porphyry in which the majority of the phenocrysts are plagioclase about 0.1 to 0.2 inch in length. The top of this group, which is overlain by the late basic breccia, is very vesicular, the vesicles averaging about 1/2 inch in diameter, but some of them may be as large as 2 inches. The filling of these vesicles is mainly chalcedony with smaller amounts of calcite. Microscopically the lower members of this group show a very fine ground-mass containing labradorite, and glass in about equal proportions, together with magnetite. Of the phenocrysts fresh, beautifully twinned labradorite-andesine ($Ab_{50}An_{50}$) crystals predominate over a few, very small crystals of augite. Thin sections of the upper, vesicular part of this group show a reddish-brown ground-mass of glass which contains only a few recognizable minerals such as andesine, an occasional augite crystal and rarely rounded olivine.

Table 2--Chemical analyses and computed norms of the lava-flows and intrusives

Compound or mineral	I	II	III	IV	V	VI
SiO_2	47.28	48.48	53.69	49.95	61.72	66.08
Al_2O_3	11.56	13.54	18.39	17.02	16.15	16.69
Fe_2O_3	3.52	3.39	3.58	4.68	2.77	1.65
FeO	5.71	5.19	3.56	3.37	1.98	1.28
MgO	13.17	12.50	3.35	5.40	3.24	1.63
CaO	9.20	7.07	5.30	6.96	3.25	3.69
Na_2O	2.73	3.37	4.90	4.23	5.86	4.52
K_2O	2.17	2.92	3.08	2.22	1.64	2.20
TiO_2	0.88	0.67	0.98	0.78	0.58	0.35
P_2O_5	0.59	0.72	1.01	0.74	0.42	0.26
MnO	0.13	0.11	0.11	....	0.08	0.06
BaO	....	....	0.49	....	0.14	0.23
H_2O+	2.96	1.86	0.84	3.56	1.13	0.96
H_2O-	....	0.24	0.11	0.88	0.42	0.12
CO_2	....	....	0.12	....	0.27	....
			Norms			
Quartz	.....	.....	.....	.....	11.51	20.82
Orthoclase	12.79	17.24	20.90	12.79	9.49	13.90
Albite	14.93	19.39	41.55	35.63	49.44	38.25
Anorthite	19.46	13.07	18.12	21.13	11.94	16.68
Corundum	.....	.....	.....	.....	0.51	0.61
Nepheline	4.12	4.83	.....	.....	....	....
Diopside	17.82	13.87	1.97	6.97	....	....
Hypersthene	.....	.....	2.36	2.93	8.66	4.76
Olivine	21.92	21.59	5.25	5.90	....	....
Magnetite	5.10	4.87	5.10	6.73	3.94	2.32
Ilmenite	1.67	1.37	1.83	1.52	1.06	0.61
Apatite	1.34	1.68	2.17	1.68	0.93	0.62
Calcite	....	....	....	....	0.50	....

I = Leucite phonolite (leucite absarokite in Iddings) from boulder in Ishawooa Canyon, H. S. Washington, U.S. Geol. Surv., Prof. Paper 99, pp. 608-609, 1917; analyst: J. P. Whitfield.

II = Labradorite-leucite-absarokite, basal lava-flow, west side of the South Fork Valley, 2 miles above Ishawooa Creek; analyst: Prof. A. H. Phillips.

III = Andesitic basalt, Group 3 of the flows, second northern tributary of Deer Creek; analyst: R. B. Ellestad.

IV = Basalt, Group 5 of the flows, location same as II; analyst: Prof. A. H. Phillips.

V = Andesite dike where the forest-trail crosses the second northern tributary of Deer Creek; analyst: T. Kameda.

VI = Quartz-diorite-porphyry, John T. Rouse, The structure, inclusions, and alteration of the Deer Creek intrusive, Wyoming, Amer. J. Sci., v. 26, p. 144, 1933; analyst: T. Kameda.

(B) Petrology--Before taking up the petrology of these flows it is necessary to consider the variations in composition of the individual groups which go to make up the early basalt sheets. Chemical analyses were made of three of the more significant groups, namely, Groups 1, 3, and 5, and are given together with the calculate norms in Table 2.

One of the most interesting of these groups is the labradorite-leucite-absarokite occurring as the basal flow in much of the area. Attention was first called to this peculiar leucite rock by Hague in 1889 about which he writes: "A specimen of basic lava --- was collected from a boulder whose precise origin was unknown. The boulder was found in the gorge of Ishawooa River (now Ishawooa Creek). --- The two porphyritic minerals, olivine and augite, lie in a ground-mass made up, for the most part, of leucite and orthoclase, very little plagioclase being present. The other minerals present are magnetite, apatite, and sparingly minute flakes of brown mica. ----- It corresponds more closely to a leucite-phonolite than to anything else" (Arnold Hague, Notes on the occurrence of a leucite rock in the Absaroka Range, Wyoming Territory, Amer. J. Sci., v. 38, pp. 43-47, 1889).

In a later paper, "Absaroka-Shoshonite-Banakite series," Iddings (J. P. Iddings, J. Geol., v. 3, pp. 935-959, and U.S. Geol. Surv., Mon. 32, pp. 326-356, 1899) described the Absarokite rock which Hague found in Ishawooa Canyon, stating that it probably occurred as a dike or intrusive mass in the region. The writer found no absarokite intrusives in this area and it is believed that the boulder analyzed and discussed by Iddings was derived from the absarokite flow of this region (In working in this area the writer was particularly impressed by the great number of fragments of absarokite in the float well below the lava-cliffs as well as being quite noticeable as boulders in the streams). A comparison of the chemical analyses of the leucite-absarokite of Hague and Iddings with the same rock the writer found in place will show that the latter differs only slightly in containing more alumina and soda and less magnesia. While no phenocrysts of plagioclase were observed in the thin sections of the writer's rock, still it was observed that there was considerable labradorite in the ground-mass as is indicated in the mode (Table 1) and hence the name labradorite-leucite-absarokite.

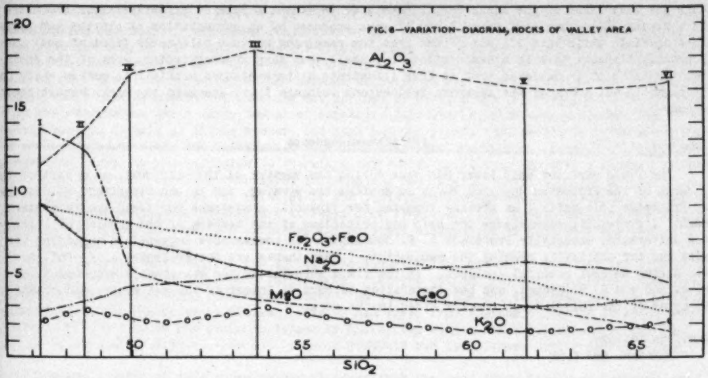
Compare, then, the analysis of this basal flow, labradorite-leucite-absarokite, with that of the analyzed rock from Group 3 of the flows (Table 2). The marked increase in silica and alumina and the sudden decrease in magnesia are most conspicuous. The analysis, showing a normative andesine together with microscopic determination of the feldspar as $Ab_{50}An_{50}$ would indicate this flow to be more andesitic than basaltic.

And finally the chemical analysis of a specimen from Group 5, a basalt, shows when compared with that of the lower flow (Group 3), a decrease in silica and alumina and an increase in iron, magnesia, and calcium. From these analyses, it is evident that these flows show no regular variations in composition corresponding to their order of extrusion, but do show a basic flow at the top and base of the series with a more acid one in a midway position.

It is believed that the flows of the early basalt sheets were all derived from a common intratelluric magma. To quote from Fenner's paper (C. N. Fenner, The Katmai magmatic province, J. Geol., v. 34, pp. 713-714, 1926) on the Katmai region: "The fact that a volcanic vent may, in the course of its history, eject lavas differing widely in composition is one of the most significant phenomena of volcanism. ---- It is now the general belief of petrologists that a single great body of intratelluric magma differentiates in some manner into various fractions, which may differ widely and yet preserve a family resemblance." The idea of a intratelluric magma as the source of these flows is substantiated by the presence of phenocrysts of olivine and augite, not only in the crystalline parts of the flows, but also in the chilled facies of these flows. This certainly indicates partial crystallization of the phenocrysts before extrusion as lava.

In making the variation-diagram, Figure 6, it was realized that such should represent more analyses than the four available for this region. (It is true that Hague, Iddings, and others have published chemical analyses from many other parts of the Absaroka Mountains and Yellowstone Region, but these are of little use in this particular problem because, so far as the writer knows, this is the first time that the early basalt sheets have been divided into these six groups and therefore the writer would not know to which group the analyses belonged. Further field-work--1933 and 1934--has shown that these same basalt sheets can be divided into similar groups throughout the entire Absaroka-Yellowstone volcanic area.) Still it would seem that some conclusions might be drawn from the limited data. In order to have all the chemical analyses of this region in one paper those of an andesite and quartz-diorite-porphyry, representative of the rocks which cut the volcanics as stocks, laccoliths, and dikes, have been included. Whether or not they are genetically related to the same magma which supplied the lava for the basalt flows is a matter for speculation because of the lack of more analyses, but their position in the variation-diagram is suggestive.

In the variation-diagram there are abrupt downslope changes in the less siliceous rocks at the left which is suggestive of settled olivine crystals and upslopes due possibly to the settling of diopside crystals.



The fact that the three analyzed flows do not show a regular variation in composition corresponding to their order of eruption does not offer serious objections to the hypothesis that the flows of this area are differentiated products erupted from a common intratelluric magma. As has been previously stated, these flows originated from many fissures or small vents scattered over the entire area and if the large magma-reservoir, which was the source of these flows, can be visualized as a mass undergoing constant differentiation, it will at once be apparent that a vertical section through this reservoir would represent a mass varying from andesitic composition at the top, to basic at the bottom. There is no reason to believe that the lava-supply, now represented in these basalt sheets, was erupted through feeders, all of which tapped the magma-reservoirs at the same horizon. On the other hand, it is quite possible that the feeders were connected to various levels of the reservoir and the varying compositions of the lava-flows of the different groups are dependent on the level at which the feeder joined the chamber. This would explain the appearance of a more acidic flow at an intermediate (stratigraphically) position in the series and would also account for more basic flows above and below it. The variation-diagram shows that these three analyzed flows could very well have originated from the same magma-chamber.

In the variation-diagram rapid drops or rises of some of the oxides are readily explained when the rock itself is examined and in most cases the answer to this is found in the petrographic descriptions of the mineral constituents which are summarized in Table 1. The relative high percentage of magnesia in IV and the lack of any olivine in this rock is explained by the high percentage (20 per cent) of augite phenocrysts in this flow. Olivine may have been present in this rock and is now represented by the mineral iddingsite which Ross and Shannon (C. S. Ross and E. V. Shannon, The origin, occurrence, composition, and physical characteristics of the mineral iddingsite, Proc. U.S. Nation. Mus., v. 67, Art. 7, pp. 1-19, 1925) suggest might be a deuteric mineral, which requires for its formation olivine of a suitable composition, a concentration of mineralizers (principally water), oxidizing conditions, and heat.

Crystallization of the lava-flows--Evidence that most of the phenocrysts were formed prior to extrusion has been given previously. In the labradorite-leucite-absarokite phenocrysts of olivine and pyroxene were the first to form, together with apatite and magnetite. Some of the olivine crystals are corroded and others are surrounded by pyroxene, and this agrees with Andersen's (Olaf Andersen, The system anorthite-fosterite-silica, Amer. J. Sci., v. 39, pp. 407-455, 1915) application of the reaction-principle to rocks containing olivine. Following the crystallization of these the magma would have a high concentration of alkalies and form the later minerals, labradorite, leucite, and orthoclase in the order named. In the other basalt flows phenocrysts of olivine, pyroxene, and plagioclase formed first and then the present ground-mass formed, the abundance of recognizable crystals of augite, plagioclase, apatite, and magnetite that formed depending on the rate of cooling and the composition of lava.

It is not the purpose of this work in which so few analyses are available to describe the process of differentiation at work in the parent magma, but attention has been called to the fact

that the lava-flows of the early basalt sheets do represent a type of differentiation and there is a strong indication that lavas I and II were produced by an accumulation of olivine and pyroxene crystals while lava III was formed from the remaining residue relatively freed of such components. Although this is a description of a small, but very representative, area of the Absaroka Mountains it is believed that it does illustrate differentiation within this series which can be found in all areas of the Absaroka-Yellowstone volcanic field wherever the early basalt sheets occur.

(V) Acknowledgments

The field work for this paper was done during the summers of 1930 and 1931, as a part of the program of the Princeton Research Party in Montana and Wyoming, and to the Department of Geology of Princeton University I am greatly indebted for financial assistance for field and laboratory work. I gratefully acknowledge the help and criticisms of the members of the faculty of Princeton University, especially Professor A. F. Buddington for innumerable suggestions regarding the work and for critically reading the manuscript. Many thanks are due Professor A. H. Phillips for making several chemical analyses. In the field work the writer was greatly assisted by K. P. Wilson and R. S. Cannon; and the cooperation of Merrill Snyder of the A-X Ranch, and Irving H. Larom of the Valley Ranch greatly aided in the work.

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PRE-TRIASSIC VOLCANIC ROCKS OF THE SOUTHERN APPALACHIANS

A. I. Jonas

(Abstract)

Volcanic rocks occur from Pennsylvania to Alabama in the Piedmont Plateau, Blue Ridge Area, and the Great Valley. They include volcanics of pre-Cambrian, Cambrian, and Middle Ordovician age. The most abundant types are basalt, andesite, rhyolite flows, tuffs, ash-beds, and bentonite. The paper will discuss the types of volcanics in the different areas, their metamorphism, the relations of volcanics to the adjoining sedimentary and igneous rocks, and the facts on which their age is based.

Volcanic rocks of pre-Cambrian age are most widespread and occur in the western Piedmont of southern Pennsylvania and Maryland and in the James River Area of Virginia. In the South Mountain-Blue Ridge uplift they extend from Pennsylvania across Maryland to central Virginia and appear in the same uplift in southwestern Virginia.

Lower Cambrian basalt flows occur near the base of the Unicoi formation from northern Virginia to Erwin, Tennessee, and also in the Unicoi of Grandfather Mountain, North Carolina.

Thin volcanics of Middle Ordovician age occur in the Quantico and Arvonia slates of the Virginia Piedmont. The possibility of an Ordovician age is suggested for the volcanics of the Virgilina Area which extends from southern Virginia across the eastern Piedmont of North Carolina and South Carolina.

Volcanic flows of Trenton age are present in the Lebanon Valley, Pennsylvania, and Middle Ordovician bentonites are found in central Pennsylvania, the Great Valley of Maryland, Virginia, Tennessee, and Alabama.

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VESTIGE OF A PLEISTOCENE THERMAL ACTIVITY IN ICELAND

Tom. F. W. Barth

Last summer (1934) I found several pieces of a brownish-red, brick-like rock in an inter-Glacial moraine deposit in Iceland. This find, it is believed, furnishes evidence for a Pleistocene thermal activity in that island.

The present-day thermal activity in Iceland is unequalled in intensity and extent. On the accompanying map (Fig. 1) all known localities of hot springs have been plotted, and in order to give a better idea of the proportions, the little square in which the legend of the map is printed has been drawn so as to represent the area of Yellowstone National Park on exactly the same scale. Since the intensity of the thermal activity is not less in Iceland than in Yellowstone, it is readily understood that the hot springs of Iceland are of great geologic importance. They are responsible for a large number of extensive deposits of chlorides, sulfates, and of native sulfur, as well as silica sinter, and last but not least, they have over large areas acted on the adjacent rocks and transformed them into clay-like substances. A question immediately presenting itself to the geologist is therefore the antiquity of this impressive thermal activity. Can it be traced farther back than those thousand and some years constituting the written history of Iceland? We do know that the lifetime of the individual springs varies considerably. Several of the voluminous alkaline springs are at least 1000 years old, but several examples are also known of springs which came into existence and entirely disappeared in less than one year.

More rational than studying the springs individually is, however, a study of the history of the general thermal activity over a larger area. Can the thermal activity, generally speaking, be traced farther back than into Viking times? So far, this has not been possible. No trace of inter-Glacial (or pre-Glacial) thermal activity was known from Iceland, although it would seem reasonable that some of the products formed by hot-spring action, like silica sinter or clay, should be present in Glacial material, if such products had been formed during Glacial times.

The whole point of this paper is now to prove that the red, brick-like rock fragments mentioned at the outset are derived from an original basalt that has been altered by hot-spring action in Glacial times.

Mode of occurrence--The moraine in which the material was found is in southwestern Iceland just south of the church at Hruni, at a slightly higher altitude than that of the highest shorelines (corresponding to the maximum Glacial submergence of the country). The place is marked with an arrow on the accompanying map (Fig. 1). The adjacent terrain is covered with marine deposits through which protrude small mountains and hillocks of basalt with interbedded Glacial material. A few outcrops of liparite have also been encountered [compare Table 1 (after H. A. Peacock, The geology of Iceland, Trans. Geol. Soc., Glasgow, v. 17, p. 198, 1925) which gives a survey of the stratigraphical subdivision of Iceland].

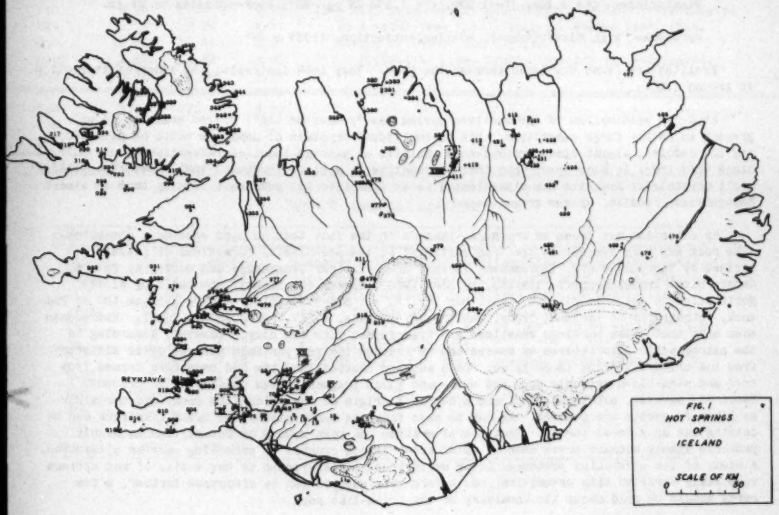

Table 1--Stratigraphical subdivision of Iceland

Formation	Igneous	Sedimentary	Age
Post-Glacial	Hot springs Active volcanoes Soda-trachyte Basaltic lava	Aeolian Alluvial Fluvio-glacial Volcano-fluvio-glacial deposits	Recent
Inter-Glacial	Ophitic basalt ("Doleritformation") Tuff and breccia ("Palagonitformation")	Conglomerate Sandstone Ground moraines	Pleistocene
	Period of volcanic rest	Marine crag of Tjörnes with molluscan fauna	Pliocene
Pre-Glacial	Basalt with tuff partings and intrusive rhyolite, granophyre, dolerite, gabbro	Conglomerate, sandstone, and clay with plant remains ("Surtarbrand")	Miocene and older

Description--The general aspect of the fragments strongly indicates their nature as fired clay; indeed, they are so unlike any natural rock that if they had not been found as constituent parts of the moraine I should surely have been deceived and regarded them as brickbats. Microscope studies of thin sections, however, revealed their nature as altered basalt: In a dense, reddish, almost opaque ground-mass, which even with the highest magnification looks rather homogeneous, are imbedded perfectly fresh and unaltered microphenocrysts of plagioclase and pyroxene. In some of the thin sections the shape and general arrangement of these phenocrysts are such that the typical ophitic-porphyritic structure of certain basalts is easily recognized. Obviously therefore the original basalt was altered in situ and the alteration product was never washed or moved before the glacier came, picked it up, and transported it to its present location.

The optical properties of the fresh phenocrysts are as follows:

Plagioclase: $\alpha = 1.565$, $\beta = 1.570$, $\gamma = 1.575$ 2V ca. 90°, corresponding to 75 An.

Pyroxene: High birefringence, oblique extinction, (+)2V = 45°.

Zeolites are found scattered through the rock. They look isotropic; the index of refraction is around 1.50.

An X-ray examination of the specimen (using the "powder-method") proved hematite to be present in rather large quantities. But no individual crystals of hematite could be detected, and the reddish, almost opaque ground-mass exhibits an average index of refraction of n = 1.71. Since this index is much lower than that of hematite it must be concluded that submicroscopically small crystals of hematite are disseminated in an aphanitic (?) substance forming thus an almost homogeneous, reddish, opaque ground-mass.

My attention was drawn by Dr. M. A. Peacock to the fact that in hand specimens the brick-like rock was very similar to the "red partings" of the pre-Glacial formations of Iceland described by Thoroddsen (Th. Thoroddsen, Island, Grundriss der Geographie und Geologie, Peterm. Geogr. Mitt. Ergänzungsheft, 152/153, p. 246, 1906), Hawkes (L. Hawkes, The building of the North Atlantic volcanic plateau, Geol. Mag., v. 3, pp. 385-395, 1916), and by Peacock (M. A. Peacock, Petrography of Iceland, Trans. Geol. Soc., Glasgow, v. 17, pp. 271-333, 1925). Thoroddsen even says that these partings sometimes are transformed into red clay. However, according to the petrographic descriptions by Hawkes and by Peacock the red partings must be quite different from the brick-like rock found by me. Both authors contend that the red beds were formed from tuff and wind-blown volcanic sand and dust--and glass fragments seem usually to be present. There is, however, nothing to indicate a detrital origin of the brick-like rock, and certainly no glass fragments are present. As may be seen from the description, the brick-like rock can be nothing but an altered basalt. That the alteration has been caused by hot springs is highly probable simply because there seem to be no other agents capable of producing such an alteration. A study of the alteration processes going on in basalts now exposed to the action of hot springs completely verifies this assumption, but before this subject can be discussed further, a few words should be said about the chemistry of the brick-like rock.

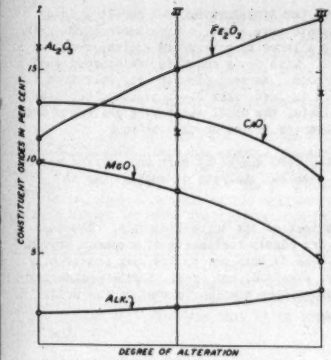

FIG. 2—GRAPHICAL REPRESENTATION OF THE ANALYSES OF TABLE 2 (I=SIDEROMELANE (TOTAL IRON HAS BEEN PLOTTED ON THE CURVE OF Fe_2O_3); II=CLAY FROM BASALT ALTERED BY HOT-SPRING ACTION; III=BRICK-LIKE ROCK)

Chemical composition--A sample of the brick-like rock gave the values listed under III in Table 2. The analyses are graphically represented in Figure 2; they will be discussed in the next section.

On clay formed by the action of thermal springs--As already mentioned in the introduction, large deposits of clay have been formed in Iceland through action of hot springs on the adjacent rocks. Basalt in various stages of this transformation can be seen, and numerous examples of unaltered basalt being gradually transformed into a plastic clay-like substance have been encountered. The alteration always starts in the glassy or micro-crystalline ground-mass, leaving the phenocrysts intact. The rock becomes soft and smeary, and thin sections cannot be made unless it is hardened by firing. Thin sections of altered basalts thus prepared are strikingly similar to those of the brick-like rock. As seen by an X-ray analysis, hematite also develops by firing; it is not present in the unheated clayey rock.

Long ago Bunsen (R. W. Bunsen, Über die Prozesse der vulkanischen Gesteinsbildung Islands,

Table 2--Chemical analyses

Compound	I	II	III
SiO_2	46.39	50.32	45.26
TiO_2	1.27	n.d.	4.46
Al_2O_3	16.27	11.66	13.74
Fe_2O_3	1.35	15.03	17.66
FeO	9.96	.....	0.13
MgO	9.77	8.26	4.57
CaO	13.00	12.61	9.18
Na_2O	1.40	1.32	2.92
K_2O	0.15	0.80	1.16
H_2O+	0.15	.....	0.72
H_2O-	0.10	.....	0.51
CO_2	nil	.....	nil
P_2O_5	0.05	.....	....
Totals	99.86	100.00	100.31

Notes:
I = Sideromelane; Gullfoss, Iceland; analyst: W. H. and F. Herdsman (M. A. Peacock, The petrology of Iceland, I. Trans. R. Soc., Edinburgh, v. 55, pt. 1, p. 57, 1926).
II = Clay from basalt; Storihnupur, Iceland (recalculated on a water-free base); analyst: Bunsen (Ann. Phys. Chem., v. 83, p. 268, 1851).
III = Brick-like rock; Hruni, Iceland; analyst: Barth.

Table 3--Chemical analyses

Compound	I	II
SiO_2	51.53	45.26
TiO_2	4.47	4.46
Al_2O_3	19.63	13.79
Fe_2O_3	23.49	17.66
FeO	0.05	0.13
MgO	0.28	4.57
CaO	0.04	9.18
Na_2O	0.25	1.92
K_2O	0.21	1.16
H_2O	....	1.23
CO_2	nil	nil
Totals	99.95	100.31

Notes:
I = Washed clay; Reykir in Ölfus, Iceland; analyst: Barth. (In order to compare this analysis with that of the brick-like material it is here given on a water-free base. The natural clay actually contains an astonishing amount of water: H_2O at 120° = 54.50 per cent, H_2O at 900° = 9.74 per cent.)
II = Brick-like rock; Hruni, Iceland, quoted from Table 2.

Ann. Phys. Chem., v. 83, pp. 197-272, 1851) observed that the transforming of a basalt to clay was no simple soaking process, but that certain constituents were added, others subtracted. His analysis of clay from the margin of a basalt dike partly altered by hot-spring action, recalculated on a water-free base, is given under II in Table 2. With it is compared the composition of an unaltered sideromelane and that of the brick-like rock. As seen particularly well from the graph (Fig. 2) the composition of the brick-like rock is just right for a basalt altered by hot-spring action. And, as seen from the following analysis, the usual weathering processes are not capable of producing such chemical changes as are observed in the brick-like rock.

Most of the clay deposited around the hot springs has been washed by rain and surface water and exposed to the various agencies of weathering. The chemical analysis of such a clay is listed under I, Table 3.

It is interesting to compare the clay analysis with that of the brick-like rock. The unusual amounts of ferric iron and of titania in both rocks are highly indicative of a common origin. Otherwise it is obvious that the surface-water has been able to soak out of the clay practically everything except the highly insoluble oxides of silicon, aluminum, and iron. Simple weathering is not capable, therefore, of producing a rock with a composition similar to that of the brick-like material.

The following facts have now been established:

(1) The brick-like rock is an altered basalt.
(2) The alteration took place in inter-Glacial (or pre-Glacial) times.
(3) The brick-like rock is practically identical with samples of fire clay formed from basalt through hot-spring action.
(4) Weathering of basalt cannot produce a rock similar to the brick-like material.

It may be concluded, therefore, that hot springs were active in Iceland as early as in Glacial times.

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THE IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS OF CENTRAL MONTANA

Esper S. Larsen, Cornelius S. Hurlbut, Jr., C. Harry Burgess, David T. Griggs, and B. Frank Buie

The study of the Highwood Mountains was undertaken by a group of men from Harvard University under a grant from the Shaler Memorial Fund of the Department of Geology. The work was under the general direction of Larsen, who, with the assistance of Norman A. Haskell, mapped most of the volcanic rocks. Hurlbut and Griggs worked mostly on the laccoliths, Burgess on the stocks, and Buie on the dikes. The party spent two summers in the field. The laboratory work is far from complete. We cooperated closely in all the work.

Location and size of the area

The Highwood Mountains are one of the many isolated mountain groups that rise above the Great Plains in Montana. They are about 100 miles east of the main front of the Rocky Mountains and are separated by a broad valley from the Little Belt Mountains, which are a long easterly projection from the main Rocky Mountains. The igneous rocks are confined to an area of about 20 by 30 miles.

General geology

The region is underlain by Cretaceous sediments which are little deformed in most places, though locally they are faulted and deformed.

The igneous rocks are of two ages separated by a considerable interval of erosion. The older group are trachyandesites or quartz latites. Intrusives of this age are almost lacking. The younger effusives are potash-rich rocks and are basaltic. Numerous stocks, laccoliths, and dikes are associated with these later volcanics.

Volcanic rocks

The older quartz latites were at one time widely distributed, as they are found underlying

the basaltic rocks in all parts of the mountains. They came over a surface of only moderate relief and for the most part not much above the surface of the present plains. The original mass was faulted and largely removed by erosion before the basaltic rocks were erupted. These quartz latites are a remarkably uniform group of effusive rocks--both lava-flows and clastic rocks. They carry a few small phenocrysts of plagioclase and hornblende, and in places of biotite and pyroxene in a submicroscopic ground-mass that must be made up of alkali feldspar and quartz.

The basaltic flows and breccias overlie an irregular surface of the quartz latites and sediments and have a maximum exposed thickness of 2600 feet. They are a rather uniform group of rocks and are characterized by abundant phenocrysts of augite, olivine, and in most specimens analcite, leucite, or pseudoleucite. The ground-mass is commonly small in amount and is made up of feldspar and dark minerals; in the analcite rocks the feldspar is in tablets and appears to be soda-orthoclase, while in the leucite rocks it is in irregular patches and appears to be oligoclase-andesine. The fresh clear analcite has an index of refraction of 1.494 and resembles leucite. It contains 4.48 per cent K_2O. It alters to a cloudy material that appears to be ordinary analcite from its index of refraction. In most specimens it shows a narrow reaction-rim made up of orthoclase in fine aggregates. Some of the so-called pseudoleucite is believed to be pseudoanalcite. It is possible that all the analcite was derived from the replacement of leucite, but it seems much more probable that it is primary. Leucite and primary analcite have not been found together.

Stocks

Six large and several smaller stock-like intrusives are present and confined to the area of the volcanic rocks. The stocks are of various shapes, and the largest underlies an area of about a square mile. The rocks of most of the larger stocks have a composition near that of the basaltic lava and are shonkinite or related rocks. They are made up over half of pyroxene and olivine with orthoclase and nepheline or its alteration products. In many places the orthoclase and altered nepheline are in the form of "pseudoleucite." In a few small patches in two of the stocks fresh leucite is the chief light mineral.

Most of the larger stocks show more or less variation. In some it is chiefly textural and the finer textured types commonly cut the coarse with sharp contacts. There is also a variation in the amount of dark minerals. In some of the bodies there are syenitic rocks and the stock of Highwood Peak is made up of quartz syenite, monzonite, and nepheline monzonite.

About six small intrusives were found cutting volcanic rocks. They are millimeter grained and are made up of pyroxene, olivine, and fresh leucite with a small amount of oligoclase molding between the other constituents. Some of the leucite crystals are altered to cloudy analcite (possibly by weathering), but none shows any alteration that suggests pseudoleucite.

Laccoliths

Ten laccoliths are exposed east and northeast of the volcanic mountains and within eight miles of them. The laccoliths intrude the flat-lying Eagle sandstone and were injected under a rather small cover of sediments. This sandstone is a competent layer underlain and overlain by shales.

The largest laccolith is Square Butte, which is about 1300 feet thick and underlies an area of about four square miles. The base is exposed but the sediments have been completely removed from the sides and top. The top is a very flat surface dipping to the southwest, formed of angular fragments and bed-rock exposures of syenite. The present top must represent the top of a hard layer overlain by softer layers and is probably near the original top of the laccolith. Square Butte is well layered and from a distance five bands, each going completely around the Butte, can be recognized. From top to bottom they are: (1) A gray layer; (2) thin layer of nearly white outcrops; (3) another light-gray layer; (4) darker gray, thin; and (5) thick, dark, gray layer at base. A detailed study of the section shows at the top nepheline-sodalite syenite with amphibole as the only dark mineral. About 150 feet below the top some augite, partly altered to biotite, comes in with the amphibole. At about 180 feet below the top is the white layer which is 40 feet thick and sharply separated from the overlying and underlying syenite. It differs from the overlying and underlying syenites chiefly in the coarser texture. Below this is syenite much like that above, but it becomes richer in augite and about 400 feet below the top augite is the only mafic mineral. In the lower part olivine joins the augite and increases in amount to the bottom of the syenite zone. The lower 600 feet of the body is shonkinite. The contact of the shonkinite and syenite is sharp and clearly shows intrusive relations.

The evidence seems to indicate that there were three intrusions: The shonkinite, the main syenite, and the thin layer of white syenite. The main syenite varies gradually from top to bottom and may have differentiated in place, although simple crystal settling cannot account for all the variation.

The Shonkin Sag laccolith is especially interesting because both the top and sides are well exposed and several gullies cut sections well into the laccolith. A section across the laccolith is:

Leucite basalt porphyry	5 feet
Shonkinite	40
Nepheline syenite	30
Intermediate rock	15
Shonkinite	120
Leucite basalt porphyry	10
Total	220 feet

The contacts between the rock types are in most places sharp; locally there is a narrow gradational zone. The intermediate rock (transitional rock of Pirsson) is a coarse rather irregular rock which might be called pegmatitic. A common feature is graphic intergrowths of augite and orthoclase about the size of walnuts. These frequently act as nuclei from which slender augite crystals radiate. In some places these augite prisms are 8 inches long making the rosettes 16 inches across. One of the curious features is a nearly horizontal layer 3 inches thick of a fine-grained nepheline-syenite that is present everywhere in the transition-rock. In places it is near the base, in others near the middle or top. In only one place does it cut for a few inches into the overlying syenite.

Five of the other laccoliths are similar to the Shonkin Sag laccolith but show less well-developed layering, possibly because they are cut only along their borders. Two of the laccoliths are of a shonkinite that carries abundant large books of biotite.

Square Butte and Round Butte are thicker than the other laccoliths and the covering rock nowhere remains. The others are very much alike in form. Their form is well illustrated by the section of the Shonkin Sag laccolith. For a short distance inward from the edge of the laccolith the thickness increases rapidly; over most of the laccolith, the top is fairly flat. Extending from the edge numerous sills intrude the sediments. At the border of the laccolith the displacement of the sediments is brought about partly by bending, partly by fracturing. The intrusion took place in several successive injections as one sill cuts another with chilled borders. The laccolith of Lost Lake shows the method of injection especially well.

Dikes

Dikes are abundant and cut the volcanic rocks, the laccoliths, the stocks, and the sediments. They are especially numerous on the eastern and northern sides of the mountains, while in other areas they are almost lacking. Only rarely are dikes found more than 12 miles from the volcanic centers from which they tend to radiate. They are in general less than 20 feet wide, and few can be followed for more than a mile.

These dikes are of various ages and five petrographic types have been recognized. The types in order of age, from the oldest to the youngest, are:

(1) Hornblende syenite porphyry--This type has phenocrysts of hornblende in a fine-textured ground-mass. Such dikes have nowhere been seen to cut the effusive analcite basalts.
(2) Olivine-rich augite basalts.
(3) Analcite-augite basalts--These are the most abundant dikes and outcrop as walls, in some places as much as 20 feet across.
(4) Minettes or biotite-rich dikes--They are abundant but outcrop poorly.
(5) Syenite porphyry, locally abundant--This type forms only very near the intrusive stocks.

Composite dikes were found in a few places. In one such a minette dike follows the border of a basalt dike for 150 feet and then cuts abruptly across it.

One dike-like body is of especial interest. It is located about 8 miles southwest of Geraldine and is very well exposed on and near the road from Geraldine to Geyser. It intrudes flat-lying sandstone. Its top is nearly horizontal but is displaced in several places by small faults. It is very well exposed in its upper part but the feeding channel and base are poorly exposed. Four trenches and a pit were dug to study the feeding channel and the lower contact.

A dike, 4 to 8 feet wide, follows above the body for its whole length and is clearly cut by it.

This body has been followed and mapped for 3-1/4 miles and goes under sediments at both ends. It clearly retains its character throughout its exposed length. West of the road this body remains covered for a distance of about 1 mile. Here its course can be partially followed by the continuation of a small anticlinal ridge of sandstone.

This body shows differentiation in place. The top foot or two is rich in pseudoleucite in crystals up to 5/8 inch across, while the main mass is a granular shonkinite. The amount of augite increases with depth. It reminds us of the description of the great dike of Southern Rhodesia, which is much longer and larger.

It might be considered as a very much elongated laccolith. A laccolith is intruded from a central plug. When it reaches a resistant layer and the overlying load is light, it lifts the layer, intrudes under it or in the lower part instead of breaking across. The body described above comes up as a dike and lifts the competent layer as a long aqueduct-like body.

Haystack Butte, near Geraldine and a little farther from the volcanic centers than most of the dikes, is cut by two irregular dike-like masses. One is a coarse melilite basalt or alnoite. The other is made up mostly of pyroxene.

Petrogenesis

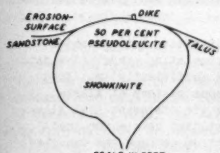
The early quartz-latite eruptions were separated from the later eruptions by a considerable interval; they are also different chemically. They resemble quartz latites of an ordinary lime-alkali series more closely than they resemble the later leucite and analcite basalts and shonkinites. They differ from the average quartz latite chiefly in their greater K_2O content. The tendency toward potash-rock had already begun but had not gone far.

The younger series, including the basaltic extrusive rocks, are characterized by some olivine, much lime pyroxene, and feldspathoid, and some feldspar low in lime.

All of the volcanic rock and the greater part of the intrusive rocks are high in mafic minerals. The felsic rocks differ from the others chiefly in their smaller content of dark minerals.

A variation-diagram of the analyzed rocks was plotted with abscissa (1/4) $SiO_2 + K_2O - CaO - MgO - FeO$. Most of the analyses fall near the generalized curve, taking into account the fact that many of the rocks were more or less altered.

The Highwood rocks differ from rocks of the lime-alkali series (dotted lines) as follows:



CROSS-SECTION OF TOP OF DIKE-LIKE BODY DESCRIBED IN TEXT ABOVE; IT IS OVER 3 MILES LONG, INTRUDES SANDSTONE, AND IS YOUNGER THAN THE DIKE ABOVE IT

Compound	Mafic end	Felsic end
SiO_2	Similar	Lower
Al_2O_3	Very low	Very high
CaO	Slightly high	Slightly high
FeO	High	High
MgO	High	Slightly high
K_2O	Very high	Very high
Na_2O	Slightly low	Slightly low

Water was high in the Highwood magmas as evidenced by the abundant analcite and the extensive metamorphism.

Compared with the Leucite Hills rocks the alumina is much higher, the soda is higher and the MgO and K_2O much lower in the Highwood rocks.

Magmatic differentiation

With the exception of the earlier quartz latite, all the igneous rocks of the area have so many features in common and the differences are so largely differences in the proportion of minerals present that a process of simple crystal settling can easily explain them. Settling of most of the early-formed pyroxene and olivine from the shonkinite would give the syenite. The process of crystal settling and floating can be shown in the dike-like body described on a previous page where the top layer is much enriched in large pseudoleucite crystals and the pyroxene increases in amount downward from the top.

For the laccoliths the problem is not so simple. The contacts of syenite, shonkinite, and other types are mostly sharp, and intrusive relations are common. The shonkinite and syenite are rather uniform rocks except in Square Butte and show no evidence of change from top to bottom. The intermediate rock is characterized chiefly by coarse pegmatitic texture and is not transitional between the shonkinite and syenite. We believe that the differentiation took place in depth and that the variations are due to successive injections. The fact that the structure of the borders of the laccolith shows several injections confirms this. The difficulty of explaining such regular layering by successive injections is great. The fracturing of the intermediate zone and injection of the 3-inch layer of syenite throughout its whole extent may give us some clue to the process.

Leucite and analcite

Leucite or analcite appear to have been abundant early minerals to crystallize from nearly all of the basalts, flows, and dikes, and probably from the shonkinites. In most of the coarse-grained rocks these minerals have been reworked by the residual magma to orthoclase and nephelite. In the early stages of this reaction the resulting mixture of orthoclase and nepheline retain the form of the leucite or analcite, but in the later stages they form a normal granular mixture in which all evidence of leucite and analcite are destroyed.

Few of the granular rocks show partial replacement of leucite by pseudoleucite, but the leucite is mostly not attacked or replaced only along a narrow border zone or else is completely replaced.

The analyses of a lava rich in fresh analcite and a small intrusive rock rich in fresh leucite are much alike, though the leucite rock has more potash and less soda. The potash in the analcite rock is probably partly in the ground-mass, which has laths of feldspar, apparently soda-orthoclase. The soda in the leucite rock is mostly in the andesine-feldspar that molds about the leucite or is in the ground-mass.

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PRE-CAMBRIAN AND PALEOZOIC VULCANISM OF INTERIOR ALASKA

J. B. Mertie, Jr.

(Published with the approval of the Director of the United States Geological Survey)

Introduction

The history of vulcanism in Alaska is a topic of great universal interest, but one which has had no adequate treatment. For some years the writer has been accumulating comparative data on this subject, and it is hoped that this information may some time be sufficiently amplified and coordinated to justify a general description of the sequential igneous history of Alaska. The scope of such an undertaking, however, can well be appreciated from the statement that Alaska is nearly a fifth the size of the United States, and that geologic studies have shown that igneous rocks have originated in Alaska in every geologic period, excepting perhaps the Cambrian and the Silurian. Therefore, in the present paper, it has seemed best to present only a part of this interesting record, and perhaps in subsequent papers to expand the areal and geologic limits of discussion.

Most of Alaska is either mountainous or hilly, but two important ranges of mountains are universally recognized, which are of an order of magnitude comparable with the Alleghany and Rocky Mountain systems in the States. In southern Alaska, the Alaska Range extends as a crescentic arc from British Columbia and southwestern Yukon Territory, to the Aleutian Peninsula, although other mountains that might more properly be designated as coastal ranges, lie between the Alaska Range and the north Pacific Ocean. In northern Alaska, the Brooks Range likewise extends across the territory, but its course, though somewhat sinuous, is more nearly east-west. Broadly speaking, all the country south of the crest of the Alaska Range, including the panhandle of southeastern Alaska, may be called southern Alaska, whereas the country north of the Brooks Range, is designated as northern Alaska. With the exception of Seward Peninsula, which is a rather distinct geographic and geologic province, all of that great region lying between the Alaska and Brooks Ranges may properly be described as interior Alaska.

Rocks of all ages, from pre-Cambrian to Recent, are found in interior Alaska, but the pre-Cambrian and Paleozoic sequences are particularly well developed. In fact, with the exception of southeastern Alaska, pre-Devonian rocks have not been recognized in southern Alaska; and the same is true of northern Alaska, though such rocks are well developed on Seward Peninsula. The geographic restriction in the title of this paper is therefore more apparent than real. Geologically, however, the scope of this discussion is markedly limited, in that the entire history of Mesozoic and Cenozoic vulcanism is not considered. This limitation is due to the fact that most of the granitic rocks of Alaska originated during these two eras, and a proper consideration of the granitic rocks alone, without reference to other types of Mesozoic and Cenozoic vulcanism, constitutes too large a subject to be included in the present paper.

Pre-Cambrian igneous rocks

The pre-Cambrian rocks of interior Alaska are at present divided into two general groups. The older of these comprises the ancient metamorphic rocks which form the base of the geologic section. These rocks, which are dominantly of sedimentary origin, are known as the Birch Creek Schist. Associated with these sedimentary schists, however, is a considerable volume of meta-igneous rocks, which are not considered to be a part of the Birch Creek Schist, though in reconnaissance geologic mapping they are not cartographically separated.

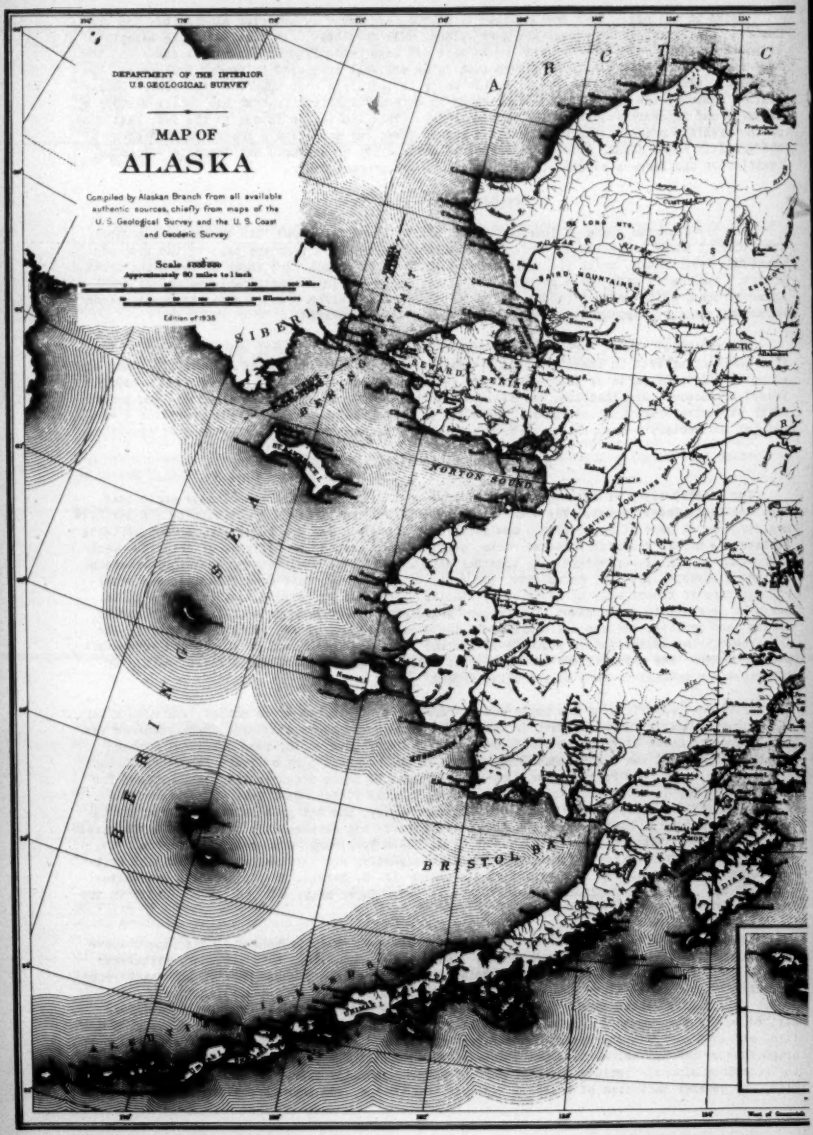
Two groups of younger pre-Cambrian rocks have also been recognized, which, however, differ from one another both in their lithologic character and in their degree of metamorphism, and also occur in different parts of the region. One of these groups consists of more or less metamorphosed arenaceous, argillaceous, and siliceous rocks, which contain little limestone and practically no contemporary igneous rocks. The other group, called the Tindir Group, contains a variety of sedimentary rocks, including much dolomite, together with several horizons of lava-flows.

Early pre-Cambrian igneous rocks

Two general types of meta-igneous rocks have been recognized that are closely associated with the Birch Creek Schist. The older of these consists in part of chlorite, albite and sericite schists, and in part of amphibolites and hornblende schists. The chlorite, albite, and sericite schists are mainly greenish foliated rocks, consisting of varying proportions of chlorite, sericite, quartz, albite, or oligoclase, together with a considerable variety of accessory minerals, including epidote, zoisite, hornblende, pyroxene, titanite, and other constituents. The amphibolites consist essentially of hornblende, biotite, albite or oligoclase, quartz, and calcite, and by a decrease in the content of feldspar, grade into the hornblende schists. The chlorite, albite, and sericite schists are confined to the upper horizons of the Birch Creek Schist, and are probably the metamorphosed products of ancient lavas and intrusives of acidic and intermediate character. The amphibolites and hornblende schists represent more basic rocks, mainly of intrusive but perhaps in part of extrusive origin.

After the deposition of the rocks now represented by the Birch Creek Schist, and also after the extrusion and intrusion of most of the meta-igneous rocks above outlined, there occurred the first major invasion of granitic rocks, of which any record has so far been obtained. These rocks occur both in the Yukon-Tanana Region, and in the adjacent part of Yukon Territory, Canada. A formational name, the Pelly Gneiss, was first applied to these rocks in the Klondike district by McConnell (R. G. McConnell, Report on the Klondike gold fields, Can. Geol. Surv., Ann. Rep., v. 14, pp. 5B-71B, 1905) of the Canadian Geological Survey; and the granite gneiss along the international boundary, southwest of the Klondike district, was subsequently correlated by Cockfield (W. E. Cockfield, Sixtymile and Ladue Rivers area, Yukon Territory, Can. Geol. Surv., Mem. 123, 1921) with the Pelly Gneiss. Subsequently, this designation was officially adopted by the United States Geological Survey in a report by the writer (J. B. Mertie, Jr., A geologic reconnaissance of the Dennison Fork district, Alaska, U. S. Geol. Surv. Bull. 827, pp. 17-23, 1931) on the Dennison Fork district.

The petrographic character of the Pelly Gneiss has been fully presented in the report above cited. Briefly the Pelly Gneiss consists of light-colored rocks that have secondary structures ranging from the regularly laminated gneissoid to the contorted schistose fabric, and these rocks therefore range from a rather massive gneiss to feldspathic quartz-mica schist, although the former is the more common type. Many of the gneisses are augen gneisses. The Pelly Gneiss is derived mainly from granitic rocks, but has also been found to include rocks of monzonitic, dioritic, and even gabbroic character. In the granitic types, the essential minerals are quartz, orthoclase or microcline, albite, and micas, of which biotite is more common than muscovite; and the accessory minerals include apatite, zircon, garnet, and magnetite. Secondary quartz, sericite, and several varieties of chlorite, epidote, carbonates, and iron-hydroxides also are present.


DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
MAP OF
ALASKA
Compiled by Alaskan Branch from all available authentic sources, chiefly from maps of the U. S. Geological Survey and the U. S. Coast and Geodetic Survey
Scale 1:2,500,000
Approximately 40 miles to 1 inch
Edition of 1935
ARCTIC
SIBERIA
BERING SEA
BERING STRAIT
SEWARD PENINSULA
NORTON SOUND
YUKON
BRISTOL BAY
ALEUTIAN ISLANDS
BROOKS RANGE
ENDICOTT MTS.
DE LONG MTS.
BALD MOUNTAIN
ARCTIC
Nome
Unalakleet
Kotzebue
Barrow
Point Hope
Wainwright
Point Barrow
Cape Lisburne
Wales
Teller
Candle
Kiana
Selawik
Shungnak
Kobuk
Noorvik
Ambler
Hughes
Allakaket
Bettles
Wiseman
Chandalar
Arctic Village
Kaltag
Nulato
Koyukuk
Galena
Ruby
Tanana
Fairbanks
Circle
Eagle
Rampart
Tanacross
Dawson
Whitehorse
Mayo
Stewart
Hazelton
Telegraph Creek
Atlin
Carcross
Skagway
Haines
Juneau
Sitka
Ketchikan
Prince Rupert
Wrangell
Petersburg
Cordova
Valdez
McCarthy
Kennecott
Chitina
Copper Center
Gulkana
Glennallen
Tok
Northway
Big Delta
Fairbanks
Nenana
Healy
Anchorage
Seward
Kodiak
Cold Bay
Dillingham
Bethel
Kuskokwim
Iditarod
Flat
Ophir
Takotna
McGrath
Tanana
Kaltag
Unalakleet
Nome
Kotzebue
Barrow
Point Hope
Wainwright
Point Barrow
Cape Lisburne
Wales
Teller
Candle
Kiana
Selawik
Shungnak
Kobuk
Noorvik
Ambler
Hughes
Allakaket
Bettles
Wiseman
Chandalar
Arctic Village
Kaltag
Nulato
Koyukuk
Galena
Ruby
Tanana
Fairbanks
Circle
Eagle
Rampart
Tanacross
Dawson
Whitehorse
Mayo
Stewart
Hazelton
Telegraph Creek
Atlin
Carcross
Skagway
Haines
Juneau
Sitka
Ketchikan
Prince Rupert
Wrangell
Petersburg
Cordova
Valdez
McCarthy
Kennecott
Chitina
Copper Center
Gulkana
Glennallen
Tok
Northway
Big Delta
Fairbanks
Nenana
Healy
Anchorage
Seward
Kodiak
Cold Bay
Dillingham
Bethel
Kuskokwim
Iditarod
Flat
Ophir
Takotna
McGrath
Tanana

O C E A N
GULF OF ALASKA
PACIFIC OCEAN
BERING SEA
PACIFIC OCEAN

In the more basic types of this gneiss, green hornblende becomes the more common mafic mineral, and titanite and magnetite become more prominent among the accessory minerals. The constant and locally high percentage of albite among the alkali feldspars of these gneisses is one of the more interesting petrographic features. It is believed that some of this albite has originated in part by albitization of preexisting plagioclase feldspars; that some of it is an original magmatic mineral; and that a third part has grown as crystalloblastic albite, the latter type of albite, however, being restricted mainly to the feldspathic quartz-mica schists.

The Pelly Gneiss has invaded the older rocks of the Birch Creek Schist, and probably is younger than all that group of rocks, though this fact has not been definitely proven by field-evidence. It definitely is not a locally metamorphosed facies of the Mesozoic granitic rocks of the region, as it has been found in an intrusive relationship to such rocks. The Pelly Gneiss, however, has not been found as an intrusive among the Paleozoic rocks, but on the other hand the early Paleozoic section is not well known in those areas where the Pelly Gneiss is typically developed. On stratigraphic evidence alone, therefore, its geologic age is not closely determinable. By McConnell and Cockfield, of the Canadian Geological Survey, the Pelly Gneiss has been considered to be a part of the pre-Cambrian sequence. This assignment harmonizes with the occurrence of granitic minerals in the arkosic sandstones of some of the later pre-Cambrian rocks of the Yukon-Tanana Region, and with the absence of contemporary gneisses among these later pre-Cambrian rocks. For all these reasons, the writer also accepts the Pelly Gneiss as a part of the pre-Cambrian sequence, believing that it is probably younger than all of the Birch Creek Schist and older than all of the later pre-Cambrian rocks of the region.

Another group of meta-igneous rocks, known as the Totatlanika Schist, occurs in central Alaska in the foot-hills along the north side of the Alaska Range. The rocks of this group consist mainly of augen gneisses and feldspathic schists, together with some interbedded tuffs and altered sedimentary rocks. The igneous members of this group have been shown to be mainly metamorphosed rhyolitic lavas. These rocks were mapped originally by Brooks and Prindle (A. H. Brooks, The Mount McKinley region, Alaska; with descriptions of the igneous rocks, and of the Bonnifield and Kantishna districts, by L. M. Prindle, U. S. Geol. Surv., Prof. Paper 70, pp. 149-150, 1911) as Paleozoic rocks, but were correlated with another group of rocks, which were classified as Silurian or Devonian. Subsequently, Capps (S. R. Capps, The Bonnifield region, Alaska, U. S. Geol. Surv. Bull. 501, pp. 22-26, 1912) applied the name Totatlanika Schist to these rocks, and in the absence of any additional evidence of their age, likewise classified them as Silurian or Devonian. No further data have been acquired regarding the age of these schists, but the Birch Creek Schist, which underlies them, is now known to be much older than was formerly supposed. Hence the Totatlanika Schist may also be older than Silurian; and it is possible, particularly in view of the acidic character of these metamorphosed lavas, that they may be the surficial equivalents of the Pelly Gneiss.

Late pre-Cambrian igneous rocks

Basic lava-flows constitute an important part of the Tindir Group, which is an assemblage of late pre-Cambrian rocks that occur a short distance north of the Yukon River, on both sides of the international boundary. In an earlier publication by the writer (J. B. Mertie, The Tatonduk-Nation district, Alaska, U. S. Geol. Surv. Bull. 836, pp. 369-392, 1933), the stratigraphic sequence of rocks comprising the Tindir Group has been shown to be as follows:

Unit A--Top of section. Principally thin-bedded limestone. Thickness about 1700 feet.
Unit B--Principally siliceous dolomite and shale, with beds of dolomitic conglomerate near the base. Thickness about 2500 feet.
Unit C--Upper red beds, consisting of hematitic dolomite, shale, flint, tuff, and lava, with a red basal conglomerate. Thickness 2200 to 2600 feet.
Unit D--Amygdaloidal and ellipsoidal lavas of greenstone habit. Thickness about 1000 feet.
Unit E--Thin-bedded dolomite, shale, argillite, and quartzite, with local beds of more massive dolomite and quartzite. Also basic dikes and sills. Thickness about 10,000 feet.
Unit F--Massive magnesian limestone and dolomite. Thickness not less than 1,000 feet.
Unit G--Thin-bedded dolomites and argillaceous not unlike those of unit E, and including one well-marked horizon of lava-flows, and one or more horizons of red beds. Unit G may be in part the stratigraphic equivalent of some of the six preceding units.

Unit D, which consists entirely of igneous material, may be taken as characteristic of these late pre-Cambrian lavas. The basal part of Unit D is composed of massive lavas, which grade upward into volcanic conglomerates and agglomerates. Most of the lavas are amygdaloidal, and some are ellipsoidal in character. Dikes and sills, which represent the principal intrusives, are more typically developed in the formations underlying unit D, particularly in unit E. These lavas

and associated intrusives are mainly basalts and diabases, which merit no detailed petrographic description. Most of the dikes and sills and some of the lavas tend toward a diabasic habit, and some of these rocks, particularly the intrusives, have a small percentage of orthoclase and primary quartz, thus showing that they belong toward the acidic end of the diabase-basalt family. The plagioclase feldspar is in large part altered to chloritic and other secondary products, but where determinable, has the composition of sodic labradorite. The pyroxene is diopsidic and in general is less altered than the feldspar. The pyroclastic members of the sequence are particularly altered, but all these rocks have a sufficient proportion of chloritic and other secondary products to be classified generically as greenstones. None of them shows any appreciable degree of dynamic metamorphism.

All the rocks of the Tindir Group, including the lavas and intrusives above described, lie below a thick series of unmetamorphosed Ordovician and Cambrian limestone, and are themselves practically unmetamorphosed, though considerably folded. This is an anachronism, when it is remembered that most of the early Paleozoic rocks of interior Alaska are greatly deformed and in part are recrystallized. And while it is not the purpose of this paper to discuss the structural geology of interior Alaska, it should be stated that these late pre-Cambrian rocks occur in an area where they have been greatly shielded from the mountain-building forces of Paleozoic and Mesozoic age, that have so greatly deformed and altered most of the other early Paleozoic and pre-Cambrian rocks of interior Alaska. These unmetamorphosed pre-Cambrian sediments and basic lavas, together with the associated basic intrusives, are certainly pre-Middle Cambrian in age, and are probably pre-Cambrian. As they contain no fossils, and as their eastward continuation into Canada has not been traced, they cannot definitely be correlated with the Beltian rocks of the Rocky Mountain Province, but their general characteristics strongly suggest this correlation.

Ordovician igneous rocks

The Cambrian and Ordovician stratigraphy of interior Alaska has not yet been carefully studied, but judging from the few areas where these early Paleozoic rocks have been examined, no igneous rocks originated during the Cambrian period, nor during the Lower Ordovician epoch. During the Middle Ordovician, however, vulcanism was renewed in interior Alaska, and a considerable thickness of lavas and tuffs was formed.

Middle Ordovician lavas have so far been identified only in the White Mountains of the Yukon-Tanana Region. These rocks consist of basic flows, tuffs, breccias, and agglomerates of greenstone habit, together with a small proportion of granular basic intrusives. The lower part of this volcanic sequence consists both of bedded lavas and interbedded pyroclastics, of greenstone habit. Amygdaloidal horizons are common, and some of the lavas are ellipsoidal. The upper part of the sequence contains an increasing proportion of volcanic conglomerate, interbedded with tuffs; and at the very top of the sequence is a bed of reddish calcareous rock, about 85 feet thick, which is believed to be a tuffaceous limestone, upon which rests a massive Silurian limestone. The thickness of this volcanic sequence is at least 2000 feet. Some gabbroic greenstones, which have a close genetic relationship to these Ordovician lavas, are also found both in the White Mountains and in the surrounding region.

These Ordovician volcanic rocks and the overlying Silurian limestone are closely folded into compressed anticlines and synclines, and at one locality the limestone is wrapped around the volcanics in a recumbent fold. As a result of such deformative stresses, the massive lava has been much fractured, and breaks into sharp angular pieces. In places the lava is mashed and slickensided, and some of the basalt has developed a well-defined secondary cleavage, so that it is really an igneous slate. Some of the fine-grained tuffaceous rocks also have a secondary cleavage. The structural features of these Middle Ordovician lavas and tuffs stand in strong contrast to the little deformed sediments and associated lavas of the Tindir (late pre-Cambrian) Group.

The red tuffaceous limestone at the top of this volcanic sequence contains marine invertebrate fossils, which have been determined to be of Middle Ordovician (Mohawkian) age. This fossiliferous horizon does not definitely determine the age of the underlying volcanic rocks, but no stratigraphic hiatus has been recognized below this horizon; and a marked disconformity does exist above this fossiliferous horizon. Furthermore, rocks which underlie this volcanic sequence contain fossils of Lower Ordovician age. It is therefore believed that this period of volcanic activity began in Middle Ordovician time, but the stratigraphic evidence does not preclude the possibility that it may have continued on into the Upper Ordovician. Though Ordovician volcanics have only been identified in the White Mountain District, it is rather likely that similar rocks of the same age will subsequently be found in other parts of interior Alaska, particularly among the undifferentiated greenstones in the region between the Yukon and the upper Kuskokwim rivers.

Lower Devonian (?) igneous rocks

Lower Silurian rocks have not been identified in interior Alaska, and middle and upper Silurian time was characterized by the deposition of thick beds of marine limestone. The evidence at present available, therefore, does not indicate the occurrence of any major vulcanism during Silurian time. Lower Devonian rocks are likewise unknown in interior Alaska, but a great structural unconformity has been recognized at various localities between the upper Silurian limestone and the overlying Middle Devonian rocks. Some time during the period represented by this unconformity, possibly in the late Silurian, but more probably in the early Devonian, it is believed that vulcanism was again renewed.

The only known locality for igneous rocks of this age is in the valley of the North Fork of Chandalar River, along the south flanks of Brooks Range. These rocks have been described by the writer (J. B. Mertie, Jr., Geology and gold placers of the Chandalar district, Alaska, U. S. Geol. Surv., Bull 773, pp. 243-244, 1925) as gneissoid rocks, which include granitic and dioritic types, but also grade into meta-igneous schists. The granitic types consist of quartz, albite, and chloritic products, with considerable secondary calcite and epidote; and the accessory minerals include apatite, titanite, and iron hydroxides. The types believed to have been derived from quartz diorite also contain quartz and albite, but contain a larger proportion of dark minerals, among which chloritized biotite and hornblende are prominent. The albite is believed to have been derived from earlier feldspars.

In this part of Alaska there is a well-defined horizon of massive limestone of late middle or upper Silurian age, known as the Skajit limestone. Stratigraphically below this formation are smaller bands of limestone, and in one of these, which is fossiliferous, the gneissic rocks were found with an intrusive relationship. These igneous rocks, originally thought to be of early Paleozoic age, therefore originated after some of the Middle Silurian rocks were laid down; and making due allowance for the depth at which they must have formed, they are probably later than the overlying Skajit limestone. The Middle Devonian rocks, above the unconformity, are much less metamorphosed than either the Silurian sediments, or the gneissic rocks, and the gneisses have not been found to intrude the Devonian sequence. It therefore seems probable that these gneisses are more or less contemporaneous with the period represented by the early Devonian hiatus in the stratigraphic sequence, though it still is possible that they are of late Silurian age. So far as known to the writer, this is the only occurrence of granitic rocks of Paleozoic age that have yet been described in any part of Alaska, but it should be emphasized that, so far as direct stratigraphic evidence is concerned, either the Pelly Gneiss or the Totatlanika Schist might conceivably be as young as late Silurian or early Devonian.

Middle Devonian igneous rocks

Basic lavas, interbedded with fossiliferous limestone and sedimentary rocks of other types, have been recognized and mapped by several geologists along the Yukon River between Eagle and Circle, and the name Woodchopper Volcanics has been applied to this group of rocks by the writer (J. B. Mertie, Jr., Geology of the Eagle-Circle district, Alaska, U. S. Geol. Surv. Bull. 816, pp. 75-80, 1930). These lavas are evidently of submarine origin, and many of the flows are ellipsoidal in character, with ellipsoidal masses in places as large as six feet in diameter. Volcanic agglomerate or flow breccia, together with some tuffaceous sediments, also form a part of the volcanic sequence. The lava itself is clearly basaltic in character, and some of it is amygdaloidal, with vesicular fillings of calcite. More or less pyrite and pyrrhotite are also distributed in these rocks.

The Woodchopper Volcanics are complexly folded and faulted, with a resulting structure that is most enigmatic, so that the stratigraphic relationship of these rocks to nearby formations of older and younger age is indeterminate. The thickness of the sequence probably amounts to several thousand feet. The fossiliferous limestones, interbedded with the Woodchopper Volcanics, indicate that this period of vulcanism occurred late in Middle Devonian time, and may have continued on into the Upper Devonian. Similar rocks, likewise closely associated with fossiliferous limestones, have also been described by the writer (J. B. Mertie, Jr., The Yukon-Tanana Region, Alaska, U. S. Geol. Surv. Bull., in preparation) some 100 miles to the westward in the hills flanking the Yukon Flats on the south. Likewise, south of the Tanana River, in the headwaters of Chisana and White rivers, Capps (S. R. Capps, The Chisana-White district, Alaska, U. S. Geol. Surv. Bull. 630, pp. 31-33, 1916) has described a volcanic sequence, consisting of 1000 to 2000 feet of basic lavas, agglomerates, and tuffs, associated with sedimentary rocks, which contain fossils determined to be of Middle or Upper Devonian age. It is probable that basic lavas of this age are widely distributed in interior Alaska, but it is only in the exceptional localities, where fossils may be found in the interbedded sediments, that the age can be definitely determined.

Upper Devonian igneous rocks

The later igneous rocks of Devonian age differ in character from any that have so far been considered, in that they are mainly intrusives and are of ultra-basic character, although they include a certain proportion of less basic rocks. The type locality for these rocks is in that area between the Yukon and Tanana rivers, generally designated as the Yukon-Tanana Region. Such rocks occur in two belts with a linear distribution. The largest and most persistent of these is a belt which begins at the Tanana River, between the mouths of Salcha and Chena rivers, and extends intermittently north 75° east to the head of Salcha River, where it is terminated by a great Mesozoic batholith of granitic rocks that lies in the central part of this region. Reappearing again on the east side of this batholith, this belt continues as intermittent masses to and probably beyond the international boundary into Canada. The other belt, which is of minor importance, crops at Livengood, and also to the east and west of that locality, with an extension westward in the valley of Troublesome Creek, in the Rampart District. Similar rocks, which may or may not be of the same age, are also found in other parts of interior Alaska.

These intrusive rocks have been little studied, and in fact few of the field occurrences have been seen by the writer. In the principal belt, however, they were examined by the writer more than 20 years ago, but their significance and age were not appreciated at the time. They form prominent ridges and buttes, barren of vegetation, with smooth rounded outlines, and a distinctive yellowish-brown color. The rocks are dominantly serpentine, greatly brecciated near the contacts, with fractured zones that are filled with calcite, quartz, and chalcedony. Some of this multi-colored fractured material may well be designated as ophicalcite. All of the main mass of serpentine does not show clearly its origin, but it is apparently derived largely from olivine-bearing ultra-basic intrusives related to dunite. Some specimens, however, are composed of olivine, altered in part to serpentine, together with tremolite and magnetite; and others are found to be derived from an olivine diabase. Still other intrusive rocks in these belts, particularly in the northern or minor belt, appear to be normal diabases in varying stages of serpentinization.

In the southern belt, these rocks are interrupted by the Mesozoic granitic rocks, thus indicating that they are older than these acidic intrusives. In the northern belt, the serpentine intrudes rocks of Middle Devonian age, but is absent in the overlying basal rocks of the Mississippian sequence. These stratigraphic relationships show definitely that the ultra-basic rocks postdate the Middle Devonian sequence, and suggest strongly that they antedate all of the Carboniferous sequence. They have therefore been referred with some assurance to the Upper Devonian. It is also of some interest to note that sedimentary rocks of Upper Devonian age are apparently absent in the Yukon-Tanana Region, where the ultra-basic rocks are typically developed, though a great sequence of Upper Devonian beds have been recognized farther north in the Brooks Range.

Carboniferous igneous rocks

It was earlier stated that the geographic limitation of this paper to interior Alaska was more apparent than real, as the pre-Cambrian and early Paleozoic rocks are typically developed in this part of Alaska. With reference to the late Paleozoic igneous rocks, however, and especially to the Carboniferous volcanics, it becomes increasingly difficult to consider interior Alaska alone, as the Carboniferous was characterized by a widespread evolution of igneous rocks. Therefore, in order to present a picture of this vulcanism in better perspective, some references will also be made to other parts of Alaska.

Carboniferous volcanic rocks have been identified in several parts of the Yukon and Kuskokwim basins, and similar rocks that are believed to be of Carboniferous age are known at many other localities in interior Alaska. The type locality for interior Alaska is a belt with a width of from 10 to 25 miles that extends from the lower end of the Yukon Flats down the Yukon Valley in a southwesterly direction for a distance of 40 miles or more. These rocks are known as the Rampart Group. A similar group of volcanic rocks are known farther up the Yukon Valley, extending from the upper end of the Yukon Flats upstream in a southeasterly direction for 20 miles or more, and cropping also in the hills west of Circle. These rocks, described by the writer (J. B. Mertie, Jr., Geology of the Eagle-Circle district, Alaska; U. S. Geol. Surv. Bull. 816, pp. 85-88, 1930) as the Circle Volcanics, are considered to be essentially contemporaneous with the Rampart Group. Another large area of volcanic rocks that are correlated with the Rampart Group begins near Ruby, and extends southwesterly as a belt from 8 to 15 miles wide for a distance of 60 miles or more. Numerous smaller areas of such rocks are known elsewhere in interior Alaska, and it is probable that these occurrences are merely remnants of more extensive lava-flows that have been in considerable measure removed by erosional processes.

The Rampart Group is an assemblage of volcanic and sedimentary rocks, with which are associated some granular intrusives. The volcanic rocks, which constitute from a half to two-thirds of the sequence, consist essentially of bedded lavas, tuffs, and breccias. The interbedded sediments include chert, shale, slate, argillite, sandstone, and a few horizons of limestone and calcareous grit. In a paper now in process of publication (J. B. Mertie, Jr., The Yukon-Tanana region, Alaska, in preparation), the writer has described the petrographic character of these rocks in some detail, but for the present purpose it suffices to state that the lavas consist mainly of basalt and diabase, of the normal type, altered to a greenstone habit. Amygdaloidal lavas are common, but ellipsoidal types are rare. Olivine is almost unknown in these rocks, but some of them carry a little accessory quartz, suggesting that they are slightly more acidic than normal basaltic types. Both the plagioclase feldspar and the pyroxene are considerably altered, the feldspar commonly more than the pyroxene. Most of the feldspar is sericitized, with the development of albite or oligoclase and kaolinic products, but the pyroxene is usually altered to chloritic minerals. Some of the basalts are partly glassy, and in such rocks the glass is commonly chloritized. The iron ores are likewise more or less altered to hematitic and limonitic products. Other secondary minerals include calcite, epidote, and various zeolites, such minerals being particularly noticeable in the amygdaloidal and tuffaceous rocks. Rhyolitic lavas and tuffs, particularly tuffs, are also present, but constitute only a small part of these volcanics, and are limited to particular small areas, rather than being distributed throughout the section.

The fragmental members of this volcanic sequence comprise tuffs of varying degrees of granularity, and still coarser grained rocks which are mainly flow-breccias. The tuffaceous rocks consist of subangular to rounded grains of volcanic material, which, however, is not only of basaltic, but also of andesitic, dacitic, and rhyolitic character. The tuffs contain some detrital quartz, and by an increase in the amount of this mineral, grade into tuffaceous sandstones. Calcite also occurs in the tuffs, and by an increase in this mineral, they grade into calcareous tuffs and tuffaceous limestones. And finally, with increasing amounts of chalcedonic quartz, probably mainly of secondary origin, the tuffs grade into cherty rocks.

Intrusive rocks constitute only a minor proportion of the igneous sequence. These include gabbro, diabase, and pyroxene diorite, which in general are less altered than the surficial volcanics. They intrude some of the lavas, and therefore appear to represent a late phase of this period of vulcanism.

The rocks of the Rampart Group are nowhere continuously exposed, and no complete stratigraphic section can be given, but from numerous incomplete and isolated sections, some idea of the stratigraphy and structure may be obtained. In general, these rocks have a regional strike of north 70° east, but are greatly folded, and at many places faulted and brecciated. The thickness can not be measured, but is estimated to be between 5000 and 10,000 feet. A few thin beds of marine limestone appear in the sequence, but the general appearance and characteristics of these rocks suggest that most of them are of terrigeneous origin.

The age of the Rampart Group is known within fairly well-defined limits. One small collection of marine invertebrates of Mississippian age was made from a thin lens of interbedded limestone and calcareous grit, and other collections of the same age have been obtained from thin subjacent horizons of similar rock. Neither the top nor the base of the Rampart Group are clearly defined, but two other Mississippian formations of non-volcanic character have been recognized in this region, one of which rests upon Middle Devonian rocks, and appears to represent the base of the Carboniferous sequence, whereas the other, from fossil evidence, represents a late Mississippian horizon. The Rampart Group has not been found in contact with either of these formations, but the structural and paleontologic relationships indicate strongly that it lies above the one and below the other. The Rampart Group is therefore considered to be entirely of Mississippian age.

A diversified section of Carboniferous rocks, including marine Upper Mississippian rocks, a terrigenous formation of Pennsylvanian (?) age, and marine Permian beds, are also known in the Yukon Valley, near the international boundary, but no lavas or volcanic material have been recognized in any of these formations. In the lower Kuskokwim Valley, however, Maddren (A. G. Maddren, unpublished notes) has reported the occurrence of a calcareous tuff, containing marine Permian fossils, which lies at the top of a formation of lava-flows. This may or may not indicate the existence of post-Mississippian vulcanism in interior Alaska.

In the Alaska Range Province, however, including in this designation the outlying ranges both to the north and south of the main range, a great thickness of Carboniferous lava-flows and interbedded sediments have been recognized. This section may be generalized in the following way:

(1) Nikolai greenstone, forming top of section. Consists wholly of thick flows of basalt, without intercalated sedimentary beds. Thickness not less than 6500 feet. Age, in part Permian, but possibly in part Triassic.
(2) Lava-flows and tuffs, with interstratified sedimentary rocks. Thickness probably 5000 feet or more. Age, Permian.
(3) Strelna Formation. Largely lavas and tuffs, with some granular intrusives, but also includes sedimentary rocks which are more prominent in the basal part of the sequence. Thickness not less than 6500 feet. Age, in part Mississippian, but possibly in part Pennsylvanian.

The type locality for the Strelna Formation is in the Kotsina-Kuskulana District, along the south slopes of the Wrangell Mountains; and the type locality for the Nikolai greenstone is in the Nizina District, farther to the east. Both these formations, however, have been studied in considerable detail in the Kotzina-Kuskulana District by Moffit and the writer (Fred H. Moffit and J. B. Mertie, Jr., The Kotsina-Kuskulana District, Alaska, U. S. Geol. Surv. Bull. 745, pp. 21-28, and 54-69, 1923), and much of the data here presented is abstracted from this report. The type locality for the intermediate unit, of Permian age, is in the headwater region of the White and Nizina rivers, where these rocks have been studied and mapped by Capps and Moffit (S. R. Capps, The Chisana-White District, Alaska, U. S. Geol. Surv. Bull. 630, pp. 33-47, 1916; Fred H. Moffit, Notes on the geology of upper Nizina River, Alaska, U. S. Geol. Surv. Bull. 813, pp. 147-152, 1930).

From the generalized section above given, together with information that is available in the publications quoted, as well as other data not yet published, it is evident that Carboniferous vulcanism took place in this part of Alaska on a far more extensive scale than in interior Alaska. At least 18,000 feet of lavas and sediments have been found, of which probably 75 per cent or more represent lavas or materials of volcanic origin. The geologic age of this great volcanic sequence is substantiated by numerous collections of marine fossils, so that the Carboniferous age of the sequence as a whole can not be doubted. Nevertheless, certain questions of age still remain to be settled. Thus, in the Strelna Formation, the stratigraphic position of the collected fossils has not been closely determined, so that the upper part of the Strelna Formation, which has relatively few sedimentary beds, may range stratigraphically upward into the Pennsylvanian. Likewise, the Nikolai greenstone, itself devoid of sedimentary beds or fossils, rests at some localities without any apparent stratigraphic hiatus upon fossiliferous Permian rocks; and at other localities is overlain disconformably by marine sediments of Upper Triassic age. It is therefore highly probable that the basal part of the Nikolai greenstone is of Permian age, but the upper part may conceivably represent some part of the Lower or Middle Triassic sequence. The final settlement of these questions is rendered more difficult by the fact that no structural unconformity has yet been recognized anywhere in Alaska, either between any of the formations of Carboniferous age, or between the Carboniferous and Triassic rocks, although both marine Pennsylvanian and marine Lower and Middle Triassic rocks are unknown in Alaska. These data indicate that, although major elevations and depressions of the land-surface took place during Carboniferous and Triassic time, these movements must have been largely of epeirogenic character. This conclusion therefore relates this major period of Carboniferous vulcanism with epeirogenic earth-movements, rather than with the deformational type of uplift and depression ordinarily associated with mountain-building.

Although it has been shown that the eastern part of the Alaska Range Province is the type locality for Carboniferous vulcanism, it should be emphasized that some part of this great volcanic sequence also occurs farther west in the Alaska Range. Likewise, about 250 miles to the southeast, in southeastern Alaska, volcanic rocks of Pennsylvanian or Permian age have been recognized by Buddington and Chapin (A. F. Buddington and Theodore Chapin, Geology and mineral deposits of southeastern Alaska, U. S. Geol. Surv. Bull. 800, pp. 109-110, 1929), and it is possible that other parts of the Carboniferous sequence are also represented. Volcanic rocks, in part assigned to the Carboniferous, and in part considered to be possibly or probably of Carboniferous age, are also known in southwestern Alaska and in Seward Peninsula. The facts at present known, however, indicate that the major locus of Carboniferous vulcanism is in the eastern part of the Alaska Range Province; that this volcanic sequence is less perfectly developed in interior and southeastern and southwestern Alaska; and that Carboniferous volcanic rocks are practically absent in northern Alaska.

Résumé

Granitic rocks have originated during at least two epochs prior to the Mesozoic era in interior Alaska. The first of these epochs of granitic intrusion took place during pre-Cambrian time, and the second probably occurred during the Lower Devonian. A third group of granitic gneisses and meta-rhyolites is also known, but the geologic age of these rocks has not been

closely determined. None of these three groups of rocks is known to have an considerable areal extent in Alaska, though the pre-Cambrian granitic rocks appear to be rather widely distributed in Yukon Territory, Canada.

Basic lavas of basaltic and diabasic character have been extruded during at least seven geologic epochs. The first two of these extrusions took place in the pre-Cambrian; the third and fourth, respectively, occurred during the Middle Ordovician and Middle Devonian epochs; and the last three happened during the three epochs of the Carboniferous. Granular intrusives of the same general character accompanied the extrusion of these lavas, but the volume of such rocks is relatively small. Some rhyolitic and dacitic lavas and tuffs are found among the Carboniferous lavas, but generally speaking lavas of acidic or intermediate character are rare. Ultra-basic rocks were intruded during the Upper Devonian epoch.

The vulcanism that occurred during the Carboniferous period was characterized by the extrusion of a great volume of basic lavas in the Alaska Range Province, but such lavas were also widely distributed in other parts of Alaska. The eruption of these lavas was accompanied by epeirogenic earth-movements that persisted into the Triassic. The Carboniferous vulcanism, both from the standpoint of volume of material erupted and of areal distribution, marks one of the greatest outpourings of lavas that has occurred in Alaska.

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IGNEOUS ASSIMILATION AND ASSOCIATED CONTACT METAMORPHISM IN THE VIRGINIA MINING DISTRICT, NEW MEXICO

Samuel G. Lasky

(Abstract)

The rocks of the Virginia Mining District consist chiefly of basalt of Comanche (?) age intruded by late Cretaceous or early Tertiary porphyritic granodiorite. The granodiorite generally has a dark border, ranging from a fraction of an inch to 20 feet in thickness, that contains a variable amount of augite and much more magnetite than the rock of the main mass. In addition, the plagioclase in the border rock is about 10 per cent more anorthitic than that in the main mass. The differences are interpreted as being the results of partial assimilation of intruded basalt in accordance with Bowen's reaction-principle.

The basalt adjacent to the contact, in a zone about 15 feet or less thick, is metamorphosed to a rock mineralogically similar to the invading granodiorite. The augite is converted to uralite, the labradorite to a less calcic plagioclase similar to that in the granodiorite, and considerable biotite, quartz, and orthoclase are present. This metamorphism is believed to have been brought about by emanations from the granodiorite at a period slightly later than the stage of magmatic assimilation. It seems to have been in general accord with the principle of reaction, the emanations having tended to convert the basalt into a rock like that from which they were derived.

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U. S. Geological Survey,
Washington, D. C.

PRE-GRANODIORITE DIKES IN GRANODIORITE, PARADISE RANGE, NEVADA

Eugene Callaghan

(Published with the approval of the Director of the United States Geological Survey)

In the course of the study of the deposits of magnesite and brucite in the Paradise Range by the Geological Survey in cooperation with the Nevada State Bureau of Mines, opportunity was afforded to map a part of a granodiorite stock and a swarm of dikes. Seven successive igneous intrusions, demonstrated by cross-cutting relationships, occur in this area of a little more than a square mile. Three distinct kinds of dike rock, andesite hornfels, andesite, and granophyre, are earlier than the granodiorite, and three kinds, malchite, mafic malchite, and rhyolite,

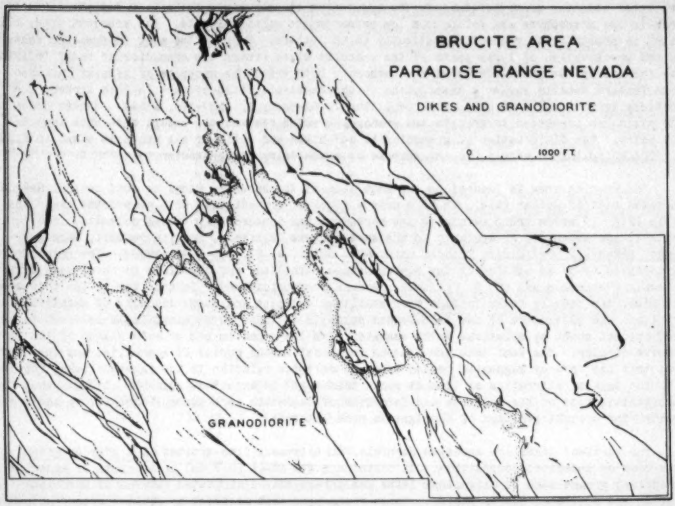
BRUCITE AREA
PARADISE RANGE NEVADA
DIKES AND GRANODIORITE
0 1000 FT
GRANODIORITE

FIG. 1

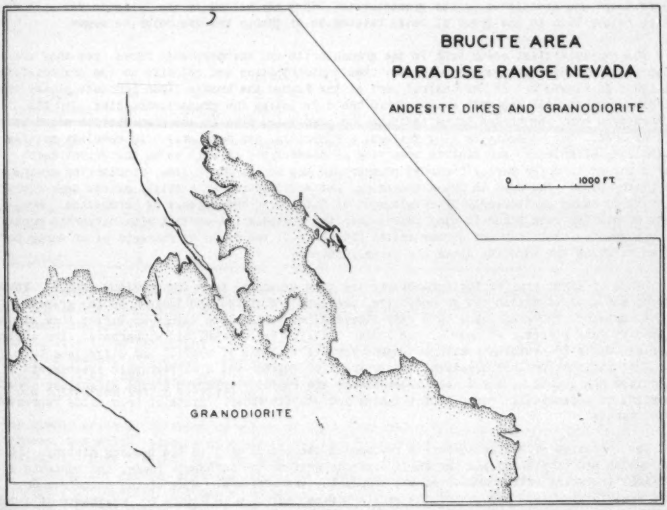
BRUCITE AREA
PARADISE RANGE NEVADA
ANDESITE DIKES AND GRANODIORITE
0 1000 FT
GRANODIORITE

FIG. 2

are later than the granodiorite. In the succession of intrusives the silica-content rises to a peak in the granophyre and falls to a low point in the mafic malchite. The youngest dike, rhyolite, is probably not related magmatically to the others. Perhaps the most interesting feature is the preservation of large parts of the andesite dikes within the granodiorite body, implying the removal by the granodiorite of the carbonate rock which the andesite originally intruded. This feature recalls Harker's description of the marscoite sills of Skye (Alfred Harker, The Tertiary igneous rocks of Skye, Mem. Geol. Surv., Glasgow, pp. 187-193, 1904). Harker shows that the sills are preserved in granite and granophyre which removed the basalt that once inclosed the sills. The distribution of granodiorite and dikes and sills of all kinds is shown in Figure 1. The stippling is merely for the purpose of emphasizing the granodiorite-contact.

The brucite area is located on the west side of the Paradise Range in west central Nevada, 45 miles east of Walker Lake. In this area a stock of granodiorite with associated dikes and sills (Fig. 1) which trend mainly to the northwest has invaded thin bedded dolomites of Upper Triassic age which dip irregularly to the west (Eugene Callaghan, Brucite deposit, Paradise Range, Nevada--A preliminary report, Univ. Nev. Bull., v. 27, pp. 1-34, 1933). The granodiorite is believed to be an outlier of the Sierra Nevada batholith, and therefore to be of late Jurassic or early Cretaceous age (H. G. Ferguson, personal communication). In addition to the thin-bedded dolomite, the country rocks include recrystallized dolomite and large deposits of magnesite and brucite. The alteration of the thin-bedded dolomite to these three minerals is believed to have been brought about by solutions which emanated from the magma in one or more stages of its intrusive history. The fact that the igneous rocks cut across bodies of magnesite, and the further fact that the form of magnesite bodies bears no definite relation to the igneous rocks, together with the lack of alteration of igneous rocks that might be expected, suggests strongly that the recrystallization of the dolomite and formation of magnesite were accomplished before the magma reached the present position of the igneous rock outcrops.

The earliest dikes are andesite hornfels, an extremely fine-grained dark gray or greenish gray rock of andesitic composition. It contains a few small (0.7 mm) phenocrysts of andesine in a modified ground-mass of oligoclase laths and irregularly distributed patches of hornblende and biotite and scattered quartz grains. These rocks have been modified by contact metamorphism due to the granodiorite intrusion. Their relation to all rocks but the andesite is definitely established by cross-cutting, and their earlier age is inferred from degree of metamorphism. Some are followed and brecciated by the granodiorite. They may belong to the Triassic volcanic sequence rather than to the group of rocks related in origin to the granodiorite magma.

The andesite-dikes occur both in the granodiorite and the carbonate rocks, yet they are invaded and brecciated by the granodiorite. Their distribution and relation to the granodiorite are shown in Figure 2. In the central part of the Figure the broken lines indicate places where the dike was not well exposed, except where the dike leaves the granodiorite-dike. In the northeastern part the broken lines indicate the brecciated dike in the granodiorite which is well exposed. The andesite is fine-grained, porphyritic, and dark gray. It consists chiefly of oligoclase, hornblende, and biotite occurring as phenocrysts as well as in the ground-mass. Quartz occurs in a few partly resorbed phenocrysts and as extremely fine interlocking grains in the ground-mass. The rock is fresh-appearing, yet modification to a slight extent near the granodiorite is shown particularly by development of biotite at the expense of hornblende. Fragments of similar rock occur in many places near the granodiorite-contact with carbonate rocks. It is suggested that they are either rafted fragments of the dikes or remnants of an early border facies to which the andesite dikes are closely related.

Dikes of light gray or buff granophyre are more extensive than the previous groups. Though they do not project within the granodiorite, they are brecciated and invaded by the granodiorite at the contact. The granophyre is a very fine-grained porphyritic flinty-appearing rock minutely jointed in most places. In some of the larger dikes it has a granitoid appearance. The analyzed material (Table 1) contains scattered phenocrysts (1 to 3 mm) of biotite and oligoclase in a matrix of sodic oligoclase crystals, mosaic areas of quartz, and a micrographic intergrowth of orthoclase and quartz. Many of the intergrowths are radially arranged around oligoclase crystals. Magnetite is essentially absent, but titanite and apatite occur. Spots of iron oxide represent former pyrite.

The intrusion of the granodiorite represents the fourth step in the igneous history. It has invaded and brecciated all the early dikes as well as the carbonate rocks, and contacts are extremely irregular with numerous dikes, apophyses, and outliers. Some of the apophyses or dikes have followed and brecciated the earlier dikes, as shown in Figure 2. Fragments of a dark, fine-grained rock, either an early border facies or fragments of the andesite dikes, occur near the contacts, though there are no comparable small fragments of the carbonate rocks. Two small

Table 1--Analyses, norms, and modes of intrusive rocks, Brucite Area, Paradise Range, Nevada

Compound or mineral	1	2	3	4	Remarks
SiO_2	53.11	61.72	65.33	73.89	George Steiger, analyst.
Al_2O_3	16.78	17.10	15.75	13.92	Norms calculated by Jewell J. Glass.
Fe_2O_3	2.06	1.78	1.92	0.73	1 = Malchite, dike, Bluestone claim.
FeO	4.98	3.10	2.42	0.55	2 = Andesite, dike, Gloria No. 3
MgO	3.84	2.90	1.82	0.61	claim, northeast of upper deposit
CaO	6.31	5.04	4.17	1.55	of brucite.
Na_2O	3.28	5.03	3.92	3.59	3 = Granodiorite, stock, Gloria No.
K_2O	2.25	1.50	2.61	4.00	3 claim, near north end of upper
H_2O+	2.90	1.05	0.76	0.91	deposit of brucite.
H_2O-	0.44	0.17	0.18	0.28	4 = Granophyre, dike, Betty O'Neal
CO_2	2.33	0.10	0.08	0.13	No. 1 claim, ridge east of upper
TiO_2	1.13	0.63	0.51	0.24	deposit of brucite.
P_2O_5	0.56	0.25	0.20	0.08	Alkali-lime index of 56.0 derived
MnO	0.10	0.10	0.07	0.02	from usual variation-diagram.
	100.07	100.47	99.74	100.30	
			Norms		
Q	11.52	11.70	20.70	34.02	
or	12.79	8.90	15.57	23.35	
ab	27.77	42.44	33.01	30.39	
an	13.62	19.74	17.51	6.39	
C	4.08	.....	.....	1.32	
wo	....	1.39	1.04	....	
en	9.60	7.20	4.50	1.50	
fs	5.68	3.30	2.24	....	
mt	3.02	2.55	2.78	0.93	
il	2.13	1.22	0.91	0.61	
ap	1.34	0.67	0.34	0.34	
cc	5.20	0.20	0.20	0.20	
			Modes		
Quartz	....	x	19.0	x	
Orthoclase	....	?	13.0	x	
Plagioclase	56.0	64.0	50.0	x	
Biotite	....	12.0	7.0	3.0	
Hornblende	....	20.0	8.0	...	
Apatite	2.0	x	x	x	
Titanite	2.0	x	x	x	
Magnetite	8.0	4.0	3.0	...	
Epidote	x	....	...	...	
Chlorite	32.0	x	x	...	
Calcite	x	....	...	...	
Sericite	x	x	x	...	

blocks of dolomite and one large block near the center of the area are surrounded by granodiorite, but they may be roof-pendants. Dikes with perthitic feldspar that occur in the brucite, a few small pegmatite-dikes, and some aplite-dikes are probably very closely related to the granodiorite. The granodiorite is of the normal type of the Sierra Nevada batholith or pluton and contains idiomorphic andesine, oligoclase, interstitial orthoclase, and about equal proportions of hornblende and biotite. Magnetite, apatite, titanite, and zircon are accessory. The rock is very fresh, and only a few little sericite and chlorite occur.

The granodiorite is followed by a host of dark dikes which might be broadly classed as lamprophyres, but which, because of their feldspathic nature and simple mineralogy, are designated malchite. They traverse both the granodiorite and surrounding rocks. They occur in two distinct groups, one earlier than the other. The earliest malchite (column 1, Table 1) is medium greenish-gray, porphyritic, and has a somewhat granular appearance, though the ground-mass is fine-grained. In one place it was found to contain partly fused fragments of granodiorite, suggesting that either the granodiorite was not entirely solid when the dike was intruded or that the initial temperature of the dike was high. The malchite is considerably altered and consists

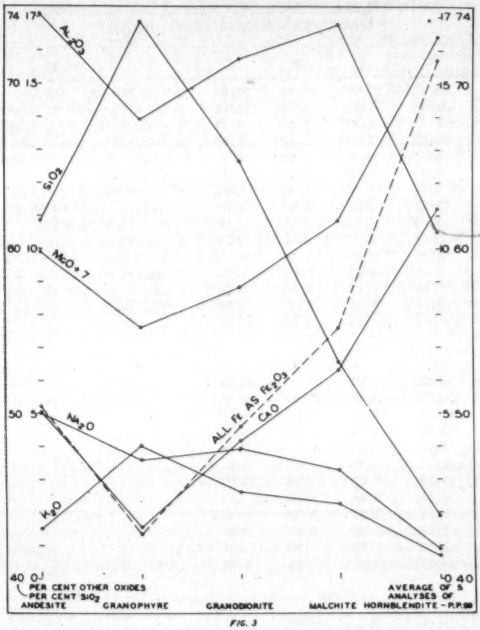

FIG. 3

largely of pseudomorphs of chlorite and calcite after hornblende, remnants of andesine surrounded by oligoclase, and some albite. Magnetite is abundant, and numerous needles of apatite and some titanite occur. Chlorite and calcite are abundant, and sericite, quartz, and epidote occur.

The later and less silicic facies of the malchite makes up the greater part of the total number of dikes. In places parallel dikes are separated by only chilled margins and a few fragments of granodiorite. The mafic malchite is dark green or greenish black, very fine-grained, and porphyritic. Most of it is considerably altered to chlorite and calcite, but an exceptionally fresh specimen was found to contain about 50 per cent of hornblende, 42 per cent of plagioclase, chiefly andesine, about 7 per cent of magnetite, titanite, and apatite, and a little quartz, biotite, and sericite.

The youngest dike is a dense light-gray rhyolite which is chiefly an aggregate of spherulites. Striated walls indicate that it was extremely viscous in the late stage of its intrusion. Two phases of the rhyolite occur in the eastern part of the area, a light-gray rock which is traversed by a darker gray rock. These dikes are probably not a part of the magmatic sequence from andesite to mafic malchite and may belong to the Tertiary volcanic epoch.

There appears to be a differentiation series in the succession of intrusions from andesite to malchite. Chemical and mineralogical variations are shown in Table 1, and chemical variations with reference to relative age are shown by the diagram (Fig. 3). In general, a moderately silicic rock (andesite) is followed by a highly silicic rock (granophyre) which is in turn followed by granodiorite and malchite in decreasing order of silica-content. The other oxides change accordingly. There is a suggestion that the end product of the differentiation series would be hornblende rock, and an analysis of the mafic malchite probably would not be greatly different from the average of five analyses of hornblendite taken from Washington's tables, shown in the

right-hand column of Figure 3. Though the number of analyses is very limited, the relatively smooth curves of the oxides and the corresponding mineralogical variation, particularly in the proportion of mafic minerals, suggests, though it does not prove, that these rocks were derived from the same magma chamber in orderly succession.

The structural relations of the granodiorite and the andesite (Fig. 2) are of particular interest in that the andesite occurs both within the granodiorite and the carbonate rocks, yet is brecciated and invaded by the granodiorite. Two interpretations may be made of this relationship. The andesite dikes are earlier than the granodiorite and originally invaded carbonate rock, which was later removed from around them by the granodiorite, leaving them in essentially their original position. This is the interpretation given the marscoite sills of Skye by Harker (Alfred Harker, op. cit., pp. 187-193). The andesite is later than the granodiorite and invaded both it and the carbonate rocks while the granodiorite was sufficiently molten to be capable of regeneration and movement and therefore able to brecciate and invade the andesite. This interpretation has been given to aplite-dikes invaded by the inclosing rock by Grout and Balk (F. F. Grout and Robert Balk, Internal structures in the Boulder Batholith, Bull. Geol. Soc. Amer., v. 45, pp. 888-889, 1934) and in a somewhat different way to lamprophyres invaded by dikes of rock similar to and apparently closely related to the inclosing rock (F. F. Grout, Petrography and petrology, pp. 189-190 and 121, 1932; Robert Balk and F. F. Grout, Structural study of the Snowbank stock, Bull. Geol. Soc. Amer., v. 45, pp. 625-630, 1934).

The first interpretation seems to accord better with observations in the field and laboratory in the area under discussion for several reasons. The andesite is fractured and fragmented in places and invaded by both pegmatitic and granitoid phases of the granodiorite. Though the original orientation of the dikes is preserved, as indicated by their continuation in the carbonate rocks, some pieces are out of position. Numerous fragments of rock very similar to the andesite occur near the contact of the granodiorite with the carbonate rock in many places, and may be fragments of the dikes that were broken off and carried by the magma. The andesite is thermally metamorphosed near the granodiorite, as indicated by the development of biotite at the expense of hornblende and a dark hornfels-like appearance in places. The fine ground-mass, zoned inclusions in plagioclase phenocrysts, and the partly resorbed quartz phenocrysts of the andesite indicate that it invaded cool rather than partly molten rocks. The granodiorite, on the other hand, has essentially the same texture at the contact as in the center of the mass, and it has granitoid and pegmatitic apophyses both in the andesite and in the other country rocks, indicating that all contiguous rocks were thoroughly heated up by the time the granodiorite reached its present position. Dikes or apophyses of granodiorite follow andesite dikes out into the carbonate rocks. They also follow and brecciate dikes of the andesite hornfels which is more extensively metamorphosed than the andesite. An interval, sufficient for the intrusion of the granophyre-dikes, elapsed between the intrusion of the andesite and the arrival of the granodiorite in its present position, for the granophyre is also brecciated by the granodiorite at the contact. The andesite is not a lamprophyre and differs from even the most feldspathic of the definitely post-granodiorite malchites in chemical and mineralogical composition and degree of alteration. Except for two areas only a few square feet in extent, no linear parallelism of platy foliation of minerals in the granodiorite was observed.

Several implications of interest attach to this interpretation. In so far as the dikes are attached to the carbonate rock they are roof-pendants, but doubtlessly many pieces are wholly unattached. The preservation of original orientation by inclusions is not an extremely uncommon feature in other areas. As the granodiorite follows the earlier dikes in places, it does not seem possible to regard the dikes as septae between separate intrusions that came in, first on one side of the dike and then on the other. If the dikes originally intruded carbonate rocks, then the latter must have been removed by the granodiorite. Some allowance may be made for forcing apart of walls, yet the disappearance of much carbonate rock must be accounted for. It did not remain in the granodiorite as fragments, nor was it incorporated chemically, for the chemical composition of the granodiorite is in no way unusual. It is suggested that magmatic solutions moved in advance of the magma, dissolved the carbonate rocks, and that these chemically modified solutions migrated outward through the country rock or up along the contact. Perhaps this may account for the enormous increment of magnesium in the remaining carbonate rocks in the form of very large deposits of magnesite and brucite and recrystallized dolomite. The calcium is not accounted for but must have been carried still farther away. The great number of dikes, especially malchite, outside of the granodiorite indicates that this is an eroded cupola of a body which is more extensive below. This is further suggested by the fact that the rhyolite has brought up fragments of granodiorite 1200 feet north of the outcrop of granodiorite.

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WELDED RHYOLITIC TUFFS IN SOUTHEASTERN IDAHO

G. R. Mansfield and C. S. Ross

(Published with the approval of the Director of the United States Geological Survey)

Rocks of rhyolitic type in eastern Idaho and adjacent parts of Wyoming were observed by the Teton Division of the Hayden Surveys under Orestes St. John (Report of the geological field work of the Teton Division, U. S. Geol. and Geog. Surv. Terr., 11th Ann. Rep. pp. 498-504, 1879), who described them as trachytes. He noted their relations to different types of underlying sedimentary rocks and their tendency to conform with the preexisting topography, but considered them all as flows.

The occurrence of welded tuffs in the Yellowstone Park Area was later noted by J. P. Iddings (U. S. Geol. Surv. Monograph No. 32, pt. 2, p. 223, 1899; also Igneous rocks, v. 1, pp. 331-332, New York, 1909), and specimens were figured by him in his book on Igneous Rocks. H. T. Stearns, in his work on the geology and ground-water resources of the Snake River Plain in southeastern Idaho and in the Mud Lake and Island Park areas of the same region, recognized such tuffs at numerous places and described them briefly in reports now in press.

G. R. Mansfield, who has worked intermittently many years in southeastern Idaho (Geography, geology, and mineral resources of part of southeastern Idaho, U. S. Geol. Surv. Prof. Paper 152, pp. 114-119, 1927; also Geography, geology, and mineral resources of the Fort Hall Indian Reservation, Idaho, U. S. Geol. Surv. Bull. 713, pp. 57-61, 1920), encountered rhyolitic rocks differing widely in texture, color, and other physical characteristics but having similar chemical composition and many similar properties when viewed in thin section under the microscope. In general these were considered and described as different colored, fluidal rhyolites, rather porous but including a few crystals of quartz and orthoclase and a little plagioclase. The presence of other minerals and of spherulitic and perlitic textures was noticed but shards were not observed or were not sufficiently conspicuous to attract attention. The rocks, therefore, aside from the obviously tuffaceous varieties, continued to be regarded as flows, as indeed their general physical appearance and behavior in the field seemed fully to justify.

As work progressed northward, nearer the borders of the Snake River Plain, the occurrences of the so-called rhyolite became more numerous, varied, and conspicuous and it was realized that their topographic position and relations to other rocks involved difficult problems. Hand specimens and thin sections from the Paradise Valley and Ammon Quadrangles, Idaho, were submitted to C. S. Ross, whose studies indicated that practically all the varieties examined by him, whether stony, glassy, or spherulitic, were originally tuffs in which the rock particles had retained their heat sufficiently after falling to become welded and solidified so that many of the resulting rocks simulated actual flows. Ross's review of specimens from localities previously described by Mansfield in the reports cited showed that some were normal rhyolite flows but others were welded tuffs.

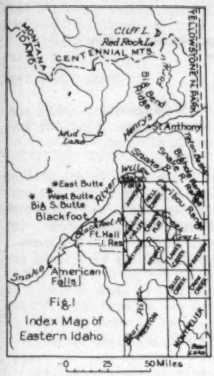
H. T. Stearns (personal communication) has suggested that the consolidation of the tuff into its present stony forms may have taken place possibly some time after its deposition by silicification and replacement through the agency of percolating waters in a manner corresponding to the chertification of limestone. The thin sections thus far studied by Ross lend no support to this view but on the contrary show definite evidence of fusion and other effects of heat.

Welded volcanic tuffs--that is, those in which individual fragments had remained plastic enough to become partly or wholly welded, or even to flow slightly after their fall--have long been recognized. Even earlier than the studies of Iddings, previously cited, W. V. Fritche and W. Reiss had described (Geol. Beschreib. der Insel Tenriff, pp. 414-422, 1868) such rocks from the Island of Teneriffe, Canary Islands. However, the wide distribution, the varied physical character, and the perfection with which the tuffaceous structures are retained appear to make the southeastern Idaho localities outstanding examples of welded volcanic tuffs.

The purpose of this paper is to describe the field-relations and petrographic character of these tuffs and to consider briefly some of the problems raised by recognition of their general character and distribution. The field-relations of the tuffs are described by Mansfield and their petrology by Ross.

Topographic relations

The occurrence of welded tuffs has been more intensively studied in the Ammon and Paradise Valley quadrangles, Idaho, than elsewhere and is believed to be typical of the region (see Fig. 1).



It is perhaps the ubiquity of the tuff that at first attracts attention. One finds it in patches, knobs, and plateau-like remnants on top of the mountains at altitudes of more than 7400 feet in the quadrangles named. St. John mentions occurrences of trachyte at altitudes of 8000 feet in neighboring areas to the northeast. Again a small knob projects from the Snake River Plain at an altitude of about 4725 feet, a mile and a half northeast of the village of Ammon.

A broad apron of tuff 1 to 3 miles wide covers the northern tip of the Blackfoot Mountains, in the Ammon and Paradise Valley quadrangles, where they begin to plunge beneath the Snake River Plain, and laps around southward into the valley of Willow Creek on the east about 12 miles. Similarly it laps southward along the west side of the mountains towards Blackfoot Valley but is not so continuously exposed. The broad apron-like exposures are augmented by numerous narrow irregular bands, where streams flowing off the mountain sides have stripped away the cover. In such situations exposures are found in different places from top to bottom along the mountain slopes. It would thus appear that the mountain mass in roughly its present form had once been sheathed with rhyolitic tuff and partly covered by later rocks or soil and then extensively stripped and eroded.

In addition to this larger scale agreement of tuff-distribution with topographic form there are numerous examples of close agreement on a smaller scale. For instance, in the Paradise Valley quadrangle rhyolitic tuff occupies much of the divide between Trail and Rawlins creeks in the central part of T. 3 S., R. 39 E. Though partly eroded or concealed by later sediments and soil it forms noteworthy dip-slopes into the valleys on either side. From this and other similar instances the material gives the appearance of having been sprayed or "ducoed," so to speak, over the surface of the country. Although there are places here and there where the tuff is thicker the rock shows a surprising degree of uniformity of thickness over wide areas and has little tendency to fill valleys or to "puddle" in former depressions.

Stratigraphic relations

Although commonly and perhaps generally associated with deposits of light-colored volcanic ash of rhyolitic composition, the welded tuff is not confined to this association but occurs also on older rocks, especially on the higher mountains. Thus it is found overlying rocks differing in age from Carboniferous to Tertiary.

The underlying ash is widespread in the two quadrangles named and in the entire region bordering the south and east sides of Snake River Valley in eastern Idaho. Its thickness in places exceeds 100 feet. It is generally well bedded with finer beds ranging from 1/8 inch to 2 inches in thickness and coarser beds ranging from 4 to 8 inches in thickness and containing fragments or pellets of pumice 1/2 to 3/8 inch in diameter. In places beds have been leached with accompanying concentration of calcium carbonate or silica in other beds. The light-colored ash beds commonly are evenly bedded, water-laid material but interbedded with them is very fine-textured, light-colored, loose sand obscurely bedded or without bedding and possibly representing wind-blown dust. The ash beds generally overlie the Salt Lake Formation (Tertiary, Pliocene?) but are locally interbedded with some of its upper members. Locally, too, beds or lenses of greenish-gray tuff with water-worn pebbles of andesite and some other rocks are included in the sequence. The later part of Salt Lake time seems to have been marked by explosive volcanic activity yielding rhyolitic ejecta and effusives.

Sequence of welded tuffs

The general sequence of the welded tuff beds is illustrated by the following section (see Plate 1).

Section of welded tuff in SE 1/4 Sec. 19, T. 2 N, R. 39 E., Ammon Quadrangle, Idaho

Tuff, highly vesicular, strongly resembling rhyolite-flow	10 feet
Tuff, resembling stony rhyolite-flow fairly free from vesicles	1.5 feet
Tuff, glassy, black, like obsidian spherulitic with spherules 2-1/2 to 3 inches in diameter	2 feet

Tuff, glassy, black, perlitic	1	foot
Volcanic ash, baked black	1	foot
Volcanic ash, whitish, grayish, yellowish with reddish streaks, cross-bedded; contains lumps of grayish-white pumice as much as 1-1/2 inches in diameter	4	feet
Total	19.5	feet

The contact of perlitic, glassy tuff with the underlying baked ash is generally sharp and somewhat irregular. The contacts between the subdivisions of the tuff are gradational. At the indicated locality the beds as a whole dip 24° southeast and strike north 65° east.

In many places there is an additional member of the series above those shown in the section given above. This is a bed 1 to 5 feet or more thick, brick red, pink, drab, or even black and breaking with conchoidal fracture into platy fragments 1 to 3 inches thick. This bed when relatively fresh has a silky luster but when weathered has a dull earthy appearance like brick. In some places different members of the sequence are absent but the black, glassy material above white or variegated ash is very common. Locally only the uppermost platy variety is present or the stony rhyolitic facies may be thicker.

Regional distribution

H. T. Stearns and others (Geology and ground-water resources of the Snake River Plain in southeastern Idaho, in press) note that on the south side of Snake River Valley, near the heads of Deep, Cottonwood, McMullen, Rock, and Dry creeks, successively farther eastward, occur thin, widespread even-bedded, fluidal pink rhyolite-flows with glassy crusts, welded tuffs and intercalated ash-beds. He states that a well-defined sequence of rhyolitic tuffs crops out at different places along Snake River between American Falls and Massacre rocks, farther southward and gives the following section.

Section of tuffs exposed at base of American Falls on north bank of Snake River

Top of section		
Red felsitic tuff containing feldspar-crystals 2 to 4 mm in length	0.6	foot
Welded rhyolitic obsidian tuff containing spherulites and lithophysae; some of the lithophysae are 3 inches in diameter	20.8	feet
Even-bedded, coarse, black ash, composed of shards of rhyolitic glass; the top layer is compact and breaks into dull obsidian fragments and grades downward into ash that can be readily removed with a knife	4.5	feet
Even-bedded gray to white rhyolitic ash, in places pisolitic	9.3	feet
Total	35.2	feet

There seems little doubt that the sequence of tuffs just described corresponds with that of the occurrences in the Ammon and Paradise Valley quadrangles farther north.

In addition to the more detailed studies made by Mansfield in the Blackfoot Mountains in the two quadrangles named, he has made reconnaissance examination of parts of other ranges farther northeast. The same appearing rhyolitic rocks in apron-like arrangement lap around the northern ends of each of them and ascend the valleys on either side for some miles along the lower slopes of the ranges. Thus the Caribou, Snake River, and Bighole ranges exhibit this feature and similar occurrences were noted near the head of the Teton Basin and along the west slope of the Teton Range extending northward toward the Yellowstone National Park. Big Bend Ridge west of Yellowstone National Park, visited in company with H. T. Stearns, exhibits similar features. On the north side of Snake River Valley in its eastern part rhyolitic rocks lap up on the slopes of the Centennial Mountains, whose crest forms the Continental Divide, and in places spread over the top on to the northern side of the range.

Farther north in Montana in areas adjoining the Red Rock lakes and in the upper Madison Valley rhyolitic rocks of similar appearance are abundant. They form the plateau in which are deeply set the gem-like Cliff and Wades Lakes (G. R. Mansfield, The origin of Cliff Lake, Montana, Bull. Geog. Soc. Phila., v. 9, No. 2, pp. 54-63, 1911). Though these occurrences have not been examined with the idea of welded tuffs in mind, it seems highly probable that many of them are of this nature.

The fact that the welded tuffs disappear beneath the Snake River Plain on the south side and that similar appearing rocks emerge from the Plain on the north side leads to the inference that they may occupy the intervening area now deeply buried beneath the basalts and sediments of the Plain itself.

It seems likely, therefore, that the area in eastern Idaho covered by rocks of this type is at least approximately 3000 square miles. If to this the areas mentioned in Montana are added, the figure might be raised to as much as 5000 square miles or more.

Possible sources

The great accumulations of rhyolitic rocks in the Yellowstone National Park naturally suggest that this area may have been the principal source of the eruptions which produced the welded tuffs and other rhyolitic rocks above described. This idea is supported by the facts that welded tuffs were early recognized in that area and that a large proportion of the original slides of Iddings have proved upon review by Ross to be indistinguishable from those in southeastern Idaho. On the other hand, quite different types are present in the Yellowstone Region, and flows are more abundant. There appears to be a distinct tendency for the tuffs to become coarser and less well sorted in the Yellowstone Region.

So far as recollection goes, it seems to Mansfield that the rhyolitic rocks of the mountain ranges in southeastern Idaho tend to thicken and become more conspicuous northeastward toward the Yellowstone Area. It seems probable, however, that the winds at the time of deposition of the welded tuffs were as now prevailingly from westerly sources. The great bulk of the region now affected by these tuffs would thus lie to windward of the Yellowstone Area and it may well be questioned how far explosions occurring in that Area could account for deposition in this region.

Other possible sources seem less adequate. For example, south of the Blackfoot River Reservoir in the Henry Quadrangle (G. R. Mansfield, The geography, geology, and mineral resources of part of southwestern Idaho, U. S. Geol. Surv. Prof. Paper 152, Pl. 3, 1927) three cones of more or less pumicious rhyolitic rock rise above the surface of the basaltic Blackfoot lava-field. These are roughly comparable in size but the largest, known for miles around as China Hat (or cap), is about a mile in diameter at the surface of the lava field and rises about 1000 feet above it. Several other lesser cones or eruptive centers occur within a few miles farther north in the same quadrangle and in the adjoining Cranes Flat Quadrangle. If the principle of prevailing wind were applied to these sources, they could supply material for areas farther northeast but not for those farther down the Snake River Valley.

Big Bend Ridge to which reference has already been made is an eastward-facing crescentic mass that may represent part of a former crater. The eastern part, however, is now missing either through down faulting or some other cause. This feature is composed in part at least of rhyolitic rocks but has not been studied in detail.

Big Southern Butte is described by H. T. Stearns (op. cit.) as composed of basalts and rhyolitic flows of different textures. The main mass is a light-colored porphyritic rock with large quartz-phenocrysts identified megascopically as a rhyolite. The bulk of the material is glassy or pumicious and obviously accumulated as explosive debris on the summit of a volcano. If a crater existed here, it has been completely dissected by erosion. The summit is composed largely of huge blocks of white pumice with a few obsidian bands. Some of the obsidian is spherulitic. In places beneath the coarse ejecta are beds of white ash and agglomerate. Big Southern Butte, which is about 21 miles southeast of Arco is about 5 miles in diameter at the base and rises about 2500 feet above the surface of the plain to an altitude of 7658 feet.

The Twin Buttes, which lie about 4 miles apart and 15 miles northeast of Big Southern Butte, are striking features of the landscape. West Butte (one of the twins) is composed of basalt but East Butte (the other twin) is composed of light-colored beds of trachyte, pumice, and obsidian dipping about 30° south and striking east. It is not itself an eruptive center but may be an eroded fault-block and is apparently of the same eruptive cycle as Big Southern Butte.

Stearns calls attention to the possibility that some of the vents may now be buried beneath the basalt flows of the Snake River Plain. He presents the hypothesis that one of the major sources of silicic flows was a chain of volcanoes extending from the Yellowstone National Park towards Boise along the axis of Snake River. This he thinks accords with all the known facts within the region though the hypothesis itself is supported by little direct evidence. Possible downwarping of the Plain prior to basaltic eruptions may account for the burial of rhyolitic cones of considerable size. He thinks that differences in the character of the rhyolitic rocks in different parts of the region accord with the view that they may have come from separate vents arranged as suggested rather than from a single restricted area such as the Yellowstone National Park.

Field-conditions affecting problems of emplacement

The emplacement of the welded tuffs presents many difficult problems. Its distribution as above outlined requires its spread as a blanket of fairly uniform thickness, 20 to 50 or more feet, conforming with considerable fidelity with preexisting topography over areas aggregating probably thousands of square miles.

The relief of the old surface with differences in altitudes of perhaps 3000 to 4000 feet indicates that the ash which formed the tuff must have been transported in considerable part through the air and deposited therefrom. The texture and composition of the mass indicates that much of it accumulated as a result of a single eruption or a group of practically simultaneous eruptions. The mass as noted grades from glassy and perlitic textures below into stony and scoriaceous textures above. A later eruption or group of eruptions, equally or more widespread, produced under comparable circumstances the uppermost or "silky" looking member of the sequence. The steps in the process appear to have been: (a) Comminution of rhyolitic magma into ash particles by frothing and explosion; (b) transportation for miles through the air; (c) accumulation to the thickness stated; (d) welding and gradational consolidation to the textures noted; and (e) interval with later eruption and deposition of "silky" tuff.

The conditions and relationships of the Idaho welded tuffs demand a heat-supply that was maintained from the time of eruption, through transportation and wide distribution, and long enough after deposition for welding and even flowage to take place. This almost stupendous supply of heat seems to indicate eruptive processes of a type or magnitude different from any that have been generally recognized, and to constitute an outstanding problem in volcanology.

Undoubtedly considerable initial heat was present at the eruptive source of the tuffs, but the presence of phenocrysts which show little or no resorption is evidence that the magma possessed little superheat. Moreover, this heat would seemingly have been dissipated within a short time, and long before the tuffs had traveled the distances that seem indicated in this region. A "nuées ardentes" type of eruption (A. Lacroix, La Montagne Pelée et ses eruptions, p. 363, Paris, 1904; Clarence N. Fenner, The origin and mode of emplacement of the great tuff deposit of the Valley of Ten Thousand Smokes, Nation. Geog. Soc. Contrib. Tech. Papers, Katmai Series, p. 74, 1923) gives a hot blast of gases that has produced remarkable heat-effects in this type of eruption. However, the very wide distribution of these welded tuffs over a great range in elevation, without any noticeable topographic control of deposition or thickness, and the marked size sorting of the fragments does not suggest a "nuées ardentes" eruption of type heretofore recognized. It seems quite probable, however, that the eruption was associated with a terrific blast of hot gases. This may help to explain a suggested source, and distribution not in agreement with the probable direction of prevailing winds.

The character and distribution of the tuffs of southeastern Idaho therefore raise serious problems as to the nature of the eruption and a heat-source adequate for their thorough welding. A definite answer to these problems is probably not possible without a better understanding of eruptive processes than we appear to possess at the present time, but certain possibilities are suggested. The differentiation processes that have produced rhyolitic and related magmas tend also to concentrate volatile elements in them (N. L. Bowen, The evolution of igneous rocks, p. 293, Princeton Univ. Press, 1928), and the violence of the explosions that produced and distributed the tuffs of southeastern Idaho is evidence of their richness in volatiles at the time of eruption. The volatile elements of a magma are not simply in solution, as water, carbon dioxide, chlorine, sulphur dioxide, etc., but are in complex chemical combination with all the different elements of the magma. There is evidence that the chemical recombinations that permit their escape as a vapor phase require time, especially in certain highly silicic rocks. The silicic character of the magma and the conditions of deposition that normally promote quick chilling should in general produce glassy rocks; and yet a large proportion of the welded tuffs has been completely devitrified. It is generally recognized that such devitrification is promoted by, and is often dependent on, the presence of volatile elements that act as mineralizers. Some of the specimens of welded tuffs show numerous large vesicules (see Plate II) that have developed subsequent to consolidation and so are definite evidence of the retention of gases until a late stage in their cooling.

A proportion of the volatile elements must have escaped at the time of explosive eruption, but some of these were clearly retained and may have been of such a chemical character as to give exothermic or heat-producing reactions during their final stages of activity. Such chemical reactions would be capable of more or less continuously supplying heat to the system, and of explaining the long maintenance of the plastic character of the tuff fragments. The question may be asked whether exothermic reactions would provide an adequate heat-increment, but on the whole

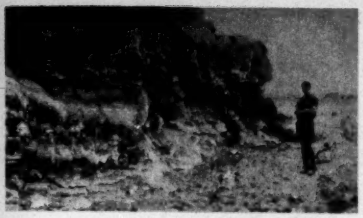


PLATE I

Plate I--Characteristic exposure of welded rhyolitic tuff in Sec. 19, T. 2 N., R. 39 E., Ammon Quadrangle, Idaho, showing irregular contact with other tuff below and gradation upward from glassy texture into perlitic, stony, and vesicular textures.

Plate II-A--Photograph of a hand specimen showing numerous spherulites and gas cavities that have developed subsequent to complete welding of plastic tuffs. Disrupted fragments of spherulites adhere to the walls of the gas cavities. These are angular in shape, some being nearly cubic; and have evidently developed by a tearing action of the expanding gases. There is thus definite evidence of the evolution of gases after deposition, welding, and consolidation of the tuffs. Natural size.

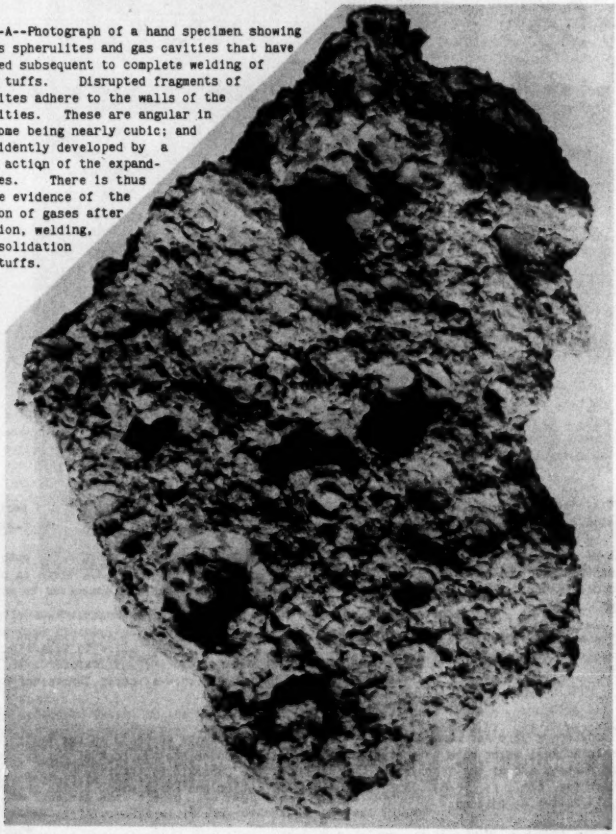


PLATE II-A

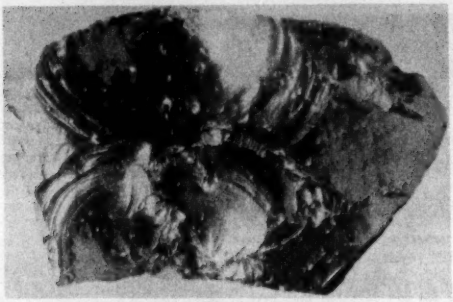


PLATE III-A

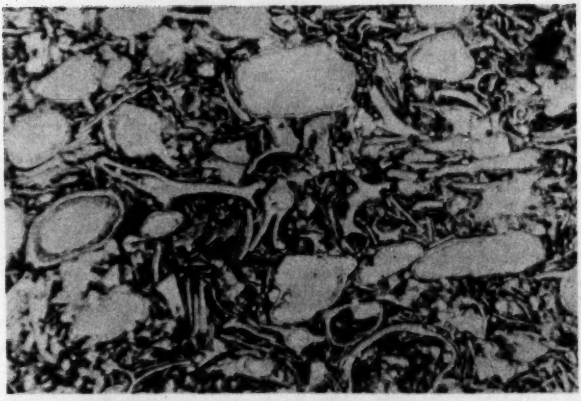


PLATE III-B

Plate III-A--Photograph of a typical obsidian with apparently complete homogeneity and perfect conchoidal fracture. The microscope, however, reveals typical tuff structures (see Plate V-B). Natural size.

Plate III-B--Microphotograph of a thin section of a glassy tuff with numerous unbroken bubbles. The individual fragments are welded together into a firmly coherent mass, but there is no marked distortion, and only slight warping of the grains to accommodate themselves to one another. x 48.

this source seems more probable than the derivation of the necessary heat wholly from that primarily present at the time of the eruption of a magma that could have possessed little primary superheat.

Comparison with other areas

The occurrence here has many parallels with the ash and pumice deposits in the Valley of Ten Thousand Smokes, which have been studied by expeditions under the auspices of the National Geographic Society and of the Geophysical Laboratory of the Carnegie Institution of Washington. C. N. Fenner (op. cit., pp. 56-60, 1923) pictures the eruption and emplacement of the great sand-flow in this valley as follows:

"When the fissures shattered the floor of the Valley the magma rose in them toward the surface but did not immediately gush out in a great flow, or swell into a pumice from the expansion

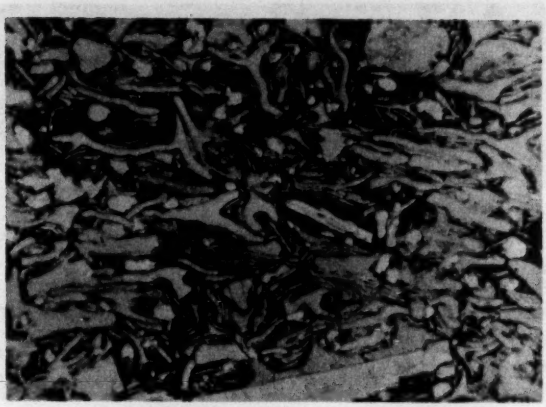


PLATE IV-A

PLATE IV-B

Plate IV-A--Photomicrograph of a glassy tuff with thorough welding, marked warping of the grains, and some flattening in the horizontal plane. At the bottom of the figure is a deeply embayed plagioclase crystal. x 48.

Plate IV-B--Photomicrograph of a welded tuff, in which warping of the grains and flattening in the horizontal plane is more pronounced than in A. x 48.

of its dissolved gases; on the contrary, sufficient time elapsed for the unconsolidated deposits at the surface to crumble down into the openings and be partly dissolved before the expansion into pumice and the resulting sand-flow occurred.

"It seems, therefore, that, although the new magma contained great possibilities of explosive action, it was not able to take advantage at once of the removal of physical restraint when the fissures were opened, but required a certain interval, presumably occupied in the rearrangement of internal equilibrium, before the violent intumescence occurred that led to the sand-flow.

"Probably the liberation of gases, even when set in full operation, required an appreciable

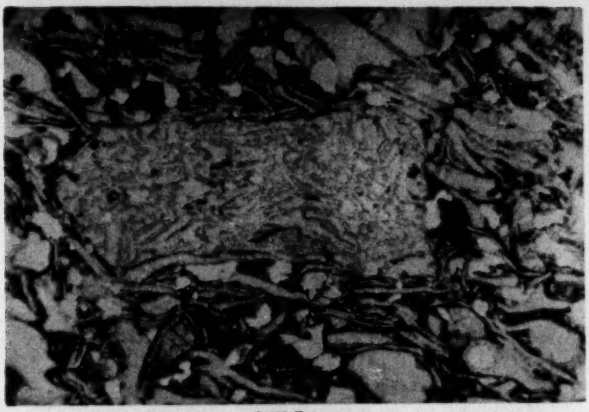


PLATE V-A

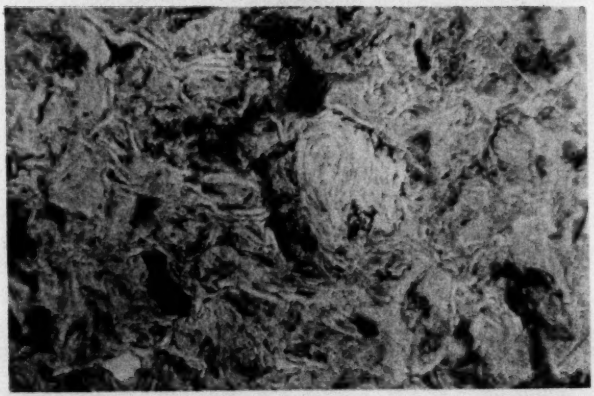


PLATE V-B

Plate V-A--Photomicrograph of a welded glassy tuff similar to Plate IV-A, but including a fragment of a more completely welded tuff. The latter is probably the result of an ash shower that fell back into the crater where it was very completely welded together. During a later eruption this material was blasted into fragments which fell together with the normal tuff-fragments. x 48.

Plate V-B--Photomicrograph of a typical obsidian (see Plate III-A). There has been very complete welding and elimination of porosity but little flattening during consolidation. x 86.

period of time, so that there was continuous evolution during the progress of the sand-flow. Thus the solid material was partly suspended in and buoyed up by the gas that it was itself evolving.*

In a later paper C. N. Fenner (Some magmatic problems, J. Wash. Acad. Sci., v. 24, pp. 113-124, 1934) emphasizes the gaseous content and assimilative activity of the magma in the Valley of Ten Thousand Smokes and describes the remarkable effects of a rhyolitic magma in the Yellowstone National Park Area in assimilating earlier formed basalt, as displayed along the Gardiner River.

PLATE XI-A

PLATE XI-B

Plate VI-A--Photomicrograph of a glassy tuff in which there has been complete accommodation of the shape of one fragment to another, elimination of pore-space, and marked flattening. Near the left center is a flattened Y-shaped grain, and just to the left of that, another elliptical grain representing an unbroken bubble. x 48.

Plate VI-B--Photomicrograph of a glassy tuff in which there has been marked flattening, and probably some flowage. However, the characteristic tuff-structures are still clearly discernible. x 48.

From these accounts it appears that rhyolitic magma "may contain within itself latent possibilities of exothermic reactions, which are developed by the change of equilibrium consequent upon its rise to the surface and the escape of volatiles."

The sand-flow of the Valley of Ten Thousand Smokes is compared by Fenner with eruptions at Mount Pelée, La Soufriere, and other volcanoes which have been called "nuées ardentes" and is considered by him as a larger scale example of this phenomenon.

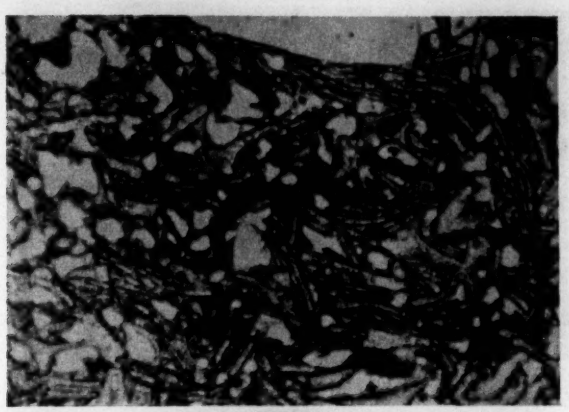


PLATE XII-A

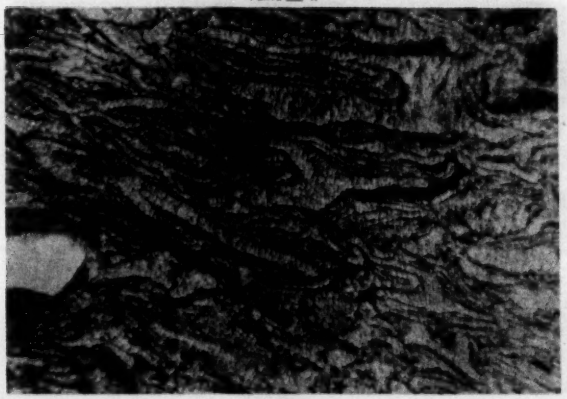


PLATE XII-B

Plate VII-A--Photomicrograph of a tuff in which there has been welding and accommodation of the form of one grain to another by warping, but only partial elimination of pore-space. Subsequent to deposition there has been devitrification so that each grain is now composed of a very fine-grained crystalline aggregate. x 48.

Plate VII-B--Photomicrograph of a tuff with complete welding and elimination of pore-space. There has been some flattening in the horizontal plane, but the characteristic tuff-structures are well preserved. Subsequent to consolidation, devitrification of the glass has produced a finely crystalline aggregate that gives the figure a granular and slightly fibrous texture. x 86.

B. N. Moore (Deposits of possible nuée ardente origin in the Crater Lake Region, Oregon, J. Geol., v. 42, pp. 358-375, 1934) describes an occurrence of pumice in the Crater Lake Region, Oregon, which he considers an example of the "nuée ardente" type of volcanic eruption. This deposit lies on an uneven surface in an area, which, to judge from his map, may have exceeded 1000 square miles and is locally as much as 60 feet thick. This Oregon occurrence is doubtless comparable to that of the Valley of Ten Thousand Smokes and probably on a considerably larger scale.

PLATE XIII-A

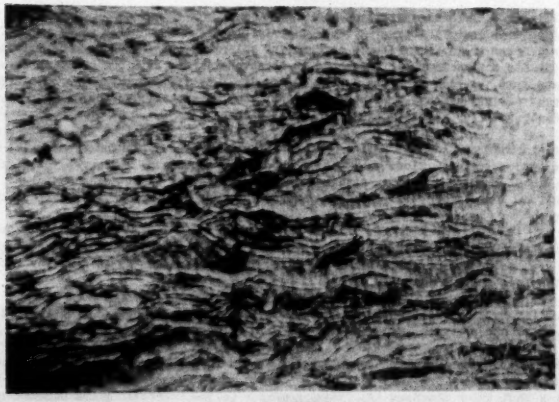


PLATE XIII-B

Plate VIII-A--Photomicrograph of a completely welded and somewhat flattened tuff. The dark areas represent small spherulites composed of an aggregate of feldspar and tridymite with radial, fibrous texture. The same structure extends into the paler colored ground-mass. The dark areas contain a black pigment while the paler ones are slightly brown and are evidently due to different states of oxidation of the iron (magnetite in the dark and hematite in the lighter areas). x 48.

Plate VIII-B--Photomicrograph of a very completely welded and much flattened tuff, which still retains characteristic tuff-structures. Subsequent to welding devitrification has produced a rock composed of a very fine-grained crystalline aggregate. x 86.

Description of welded tuffs

The welded tuffs of southeastern Idaho vary widely in external appearance. The color is most commonly some shade of gray or red, but the obsidians are black. Both stony and glassy types are present. Many of the stony ones are entirely similar to finely crystalline rhyolite-flows, with no external evidence of pyroclastic origin, but some contain angular inclusions of rock of a different color or texture, and others contain small pumice-grains, visible with a

pocket lens. The glassy types are in part typical obsidian, but others have a granular habit and resemble fine-grained quartzitic sandstones in texture. A few are highly porous and approach indurated volcanic ash in texture, but more commonly they are dense fine-grained rocks, and some of the obsidian has lost all porosity. The pore-space is primary in some materials, being due to incomplete welding and consolidation; but in others it is secondary and is due to the development of gas cavities subsequent to complete welding. These cavities vary up to 25 cm in diameter, and are most abundant in rocks with a large proportion of spherulites or in those that have become completely lithoidal.

In some specimens these cavities have developed with spherulites as a locus (see Plate II) but others in evenly lithoidal types of rock show no local development of crystals.

The spherulites are very sparse in some of the obsidians, but in other specimens they make up almost the entire rock. They vary in size from 1 or 2 mm up to a maximum of at least 7 cm, and all show a radial arrangement of the minerals. The glassy types all contain circular fractures that give a perlitic texture. This is obscure and only observable under the microscope in the obsidian types, but in some specimens it is so evenly and perfectly developed as to give the rock a fish-roe texture.

A small proportion of phenocrysts is present in all types, but varies from a few per cent up to a maximum of about 25 per cent of the rock. The dominant phenocryst mineral is oligoclase, but small amounts of quartz and orthoclase are always present and augite is in a few specimens.

Megascopic character of representative specimens

A specimen from the central part of Sec. 30, T. 1 N., R. 40 E., Ammon Quadrangle, represents the glassy type with granular texture. The color is brownish red, due to small proportion of distinctly red-brown grains distributed through the colorless ones. Angular inclusions up to 8 mm across indicate a pyroclastic origin, and an occasional grain with pumice texture is visible under the hand lens. A rock from the SW 1/4 NW 1/4 Sec. 26, T. 1 N., R. 38 E., Ammon Quadrangle, is gray without inclusions that indicate pyroclastic character, but has the same granular texture. See Plate VI-A for description of microscopic character.

Another glassy type from the NW 1/4 Sec. 10, T. 2 S., R. 39 E., Ammon Quadrangle, is dull black in the hand specimen. Close examination shows that it is made up largely of glassy perlitic grains, about 1 mm in diameter, with a few spherulitic ones about twice as large. A very large spherulite, 7 cm across, has developed across the perfectly welded, but well preserved, tuff structure.

Another glassy specimen from the NW 1/4 Sec. 10, T. 1 S., R. 40 E., Ammon Quadrangle, is light gray, with very perfect, even-sized perlitic grains about 1.5 mm in diameter that give the rock a fish-roe texture (see Plate IV-A).

The obsidian type is represented by a specimen from the SW 1/4 Sec. 30, T. 1 N., R. 40 E., Ammon Quadrangle, and pictured and described in Plate III-A and Plate V-B.

The porous type with ash-like appearance but welded into a coherent mass is represented by a specimen from the NW 1/4 Sec. 26, T. 1 N., R. 38 E., Ammon Quadrangle (see Plate III-B). This is a pink rock that under the hand lens shows numerous hollow, unbroken glass bubbles up to 1 mm in diameter. A specimen from the NW 1/4 Sec. 18, T. 1 S., R. 39 E. (see Plate VII-A) is similar in appearance.

A specimen from the SE 1/4 Sec. 25, T. 1 S., R. 38 E., Ammon Quadrangle (see Plate IV-B), has a stony appearance, but examination with the hand lens reveals a few pumice grains included in the even-grained ground-mass.

A specimen from the NW 1/4 SW 1/4 Sec. 34, T. 1 S., R. 38 E. (see photomicrograph Plate V-A) is dull gray with numerous phenocrysts and black masses of glass 1 to 3 mm in diameter that suggest a pyroclastic origin.

The stony devitrified types are represented by three specimens from the NE 1/2 of the SE 1/4 Sec. 19, T. 2 N., R. 39 E., Ammon Quadrangle, that are illustrated in Plate VII-B and Plates VIII-A and B. These are dull-gray stony appearing rocks with a few visible spherulites.

While a few specimens are obviously well indurated tuffs, and others contain inclusions that suggest a pyroclastic origin, the presence of well-preserved tuff-structure in all types of these

rocks comes as a distinct surprise on examination under the microscope. Notwithstanding the wide variation in the secondary characteristics visible in the hand specimens, there are very limited variations in the primary tuffaceous structures, when allowance is made for distortion during welding and consolidation. The average diameter of grains in nine measured sections varied from 0.04 to 0.07 mm and was 0.1 in only two. The degree of uniformity in size is illustrated in Plates III to VIII. There is a great variation in the amount of distortion that the grains have undergone. In a few specimens the original forms are unmodified; in others there is slight warping, as one plastic grain accommodated itself to another; in many there is marked flattening, but without obliteration of characteristic ash-structures; and in a few, extreme flattening and slight flowage have almost obscured the original structure. There is no essential difference in structures in the glassy and stony types, although in the stony ones dispersal of light by the fine-grained mineral aggregates makes them more difficult to photograph. In a few sections this crystallization has so obscured the structures that the original character of the rock is not evident from microscopic examination.

The most abundant types of ash structures are those that are derived from bubbles of nearly equal dimensions in different directions and are represented by nearly spherical unbroken bubbles, Y-shaped forms where three bubbles met, and crescent-shaped forms representing fragments of bubble-walls. There is commonly a small proportion of pumice-grains with the fibrous structure produced by small greatly elongated bubbles. These grains are commonly larger than the more abundant type and show little distortion in the presence of great distortion and marked welding of the others. This indicates that the pumice was less plastic at the time of deposition and suggests strongly that pyroclastic materials have been derived from at least two distinct centers that were in eruption at the same time.

In a few specimens the grains are dominantly pumiceous in habit. Pumice-grains are more abundant and larger in size in the Iddings sections from the Yellowstone Region and many are almost exclusively of that type.

The spherulites and crystalline ground-mass resulting from the devitrification of the glassy material is in general too fine-grained to determine the individual minerals, but some of it is clearly composed of a mixture of alkalic feldspar and a smaller proportion of tridymite. The low aggregate-index of refraction of the fine-grained portion indicates that it has the same mineral composition and is also feldspar and tridymite.

The minerals are all fresh and without alteration, but in a few specimens secondary calcite has been introduced.

U. S. Geological Survey,
Washington, D. C.

FISSURE ERUPTIONS OF THE INDEPENDENCE PASS DISTRICT, SAWATCH RANGE, COLORADO

W. S. Burbank and E. N. Goddard

Introduction

The general conclusions set forth in this paper are based on about five days' underground study and mapping of the Twin Lakes Diversion-Tunnel, which was recently completed to divert water from Lincoln Gulch, on the west slope of the Sawatch Range, to the North Fork of Lake Creek, a tributary of the Arkansas River, on the east slope. The surface geology of the region was studied before the driving of the tunnel by J. W. Vanderwilt and A. H. Koschmann (Geology of the Independence Pass District, Colorado, U. S. Geol. Surv., preliminary report, mimeographed form No. 67484, 1932), and the general correlation of the tunnel-section with the surface geology is based on the results of this work and consultation with the authors. More details regarding the general geology of the region are given in the report cited and in a report by J. V. Howell (Twin Lakes District of Colorado, Colo. Geol. Surv., Bull. 17, 1919) covering the region east of the Continental Divide.

Geologic formations in the Tunnel

Pre-Cambrian formations--The pre-Cambrian formations exposed in the diversion-tunnel need no special description for the purpose of this paper. The rocks were mapped and classified under the following divisions: Schist (or gneiss); hornblende gneiss; granite gneiss; granite; and pegmatite and aplite.

Gradations exist between the granite gneiss and the schist, resulting either from intimate injection or from granitization of the schist. These pre-Cambrian formations are chiefly confined to the eastern portion of the Tunnel and extend from the east portal westward for about 13,400 feet.

Tertiary formations--The subdivisions of the Tertiary formations are based chiefly on observed relations in the Tunnel, and have not been satisfactorily correlated with the divisions of the surface-rocks, but further microscopic and comparative studies will probably clear up some uncertainties.

Breccia--A formation composed of pre-Cambrian debris classified as breccia by Vanderwilt and Koschmann (op. cit., p. 3) occupies a wide surface-area south of the tunnel-line. It underlies the lowest rhyolite bodies and also occurs between flows as a flat body thinning northwestward. Lithologically this rock is identical with the tectonic breccia found at the tunnel-level and is described below in connection with structural features in the Tunnel.

Fluidal rhyolite breccia--The term "fluidal rhyolite breccia" is used to avoid the terms "flow-breccia" or "intrusive breccia" and applies to a rhyolite-magma that has consolidated with numerous suspended inclusions. This rock and the tectonic breccia described below form the tunnel-walls between points about 8300 and 15,800 feet east of the west portal. Locally the fluidal base of the rocks is characterized by lenticular patches an inch or two long that represent stretched portions of the base that have solidified at stages of crystallinity different from the mass of the magma.

Most of the inclusions are foreign, consisting of granite, schist, and other metamorphic rocks, although there are some inclusions of rhyolitic material. In places these foreign inclusions are so closely packed that the rhyolite is subordinate in amount and occurs as thin irregular stringers between the fragments. In such places many of the fragments are large, commonly 5 to 15 feet in diameter, and locally the rhyolite wraps around huge blocks of granite or schist 50 feet in diameter.

This fluidal rhyolite-breccia corresponds undoubtedly to the Grizzly Peak rhyolite of J. V. Howell (op. cit., p. 1), and to the common rhyolite of the Independence Pass District. At most places where the rock is exposed in the Tunnel it is some shade of gray, though locally it is bleached, chalky, and soft, because of kaolinization. J. W. Vanderwilt and A. H. Koschmann (op. cit., p. 4) describe the common rhyolite above the Tunnel as follows: "The rhyolite is predominantly pinkish, but in the western part of Independence Mountain and farther west it is light gray. It consists of phenocrysts of quartz, feldspar, and biotite embedded in a dense ground-mass, and contains numerous inclusions of pre-Cambrian rocks, especially gneiss and granite, and fragments of chilled rhyolite. These inclusions are mostly an inch or less in size, but a few are 5 to 8 feet in diameter.

"In many parts of the District and especially near the base of the formation the rhyolite is vesicular. The vesicles may be 2 inches in length but most commonly are half an inch or less. Banding is present but is not common. A characteristic feature of the rock is its sheeted structure, which causes the rock to split into thin slabs 1 to 6 inches thick."

The vesiculation is less apparent in the Tunnel, but the lenticular patches in the base probably represent filled incipient vesicles and surficial weathering may accentuate the vesicular texture by removal of some minerals of the lentils.

Smaller rhyolite-bodies in the Tunnel occur as dikes and sheets intrusive into the pre-Cambrian rocks. These rhyolites vary in texture and may or may not have many suspended inclusions, as in the more typical fluidal breccia. Some of the bodies are composed chiefly of obsidian and resemble in texture the basal member of the Grizzly Peak rhyolite as described by Vanderwilt and Koschmann (idem, p. 4). They state:

"In many places throughout the Area the basal member of the rhyolite is a dark-gray to black, more or less glassy rock, which attains a maximum thickness of about 50 feet and is best seen on the divide near the head of Mountain Boy Gulch. In several places this rock occurs in the form of dikes, and it may therefore be encountered locally in the tunnels. It contains numerous crystals of quartz, feldspar, and biotite embedded in a dense to glassy ground-mass. It contains inclusions of pre-Cambrian gneiss and granite, most of them less than 2 inches, though some are 5 feet in diameter."

The tunnel-section affords no evidence to indicate that these smaller intrusive bodies are other than normal textural variations of the common rhyolite magma.

Rhyolite-porphyry--A body of porphyritic rhyolite occupying a position from 6100 to 8300 feet east of the west portal is chilled at its contact with the main body of the fluidal rhyolite breccia lying east of it and was mapped as a separate body. It is a porphyritic mica rhyolite whose texture ranges from structureless to distinctly fluidal. It contains lentils and vesicular zones, like the normal rhyolite-magma, and locally many inclusions, though it is freer of inclusions than the body of the fluidal rhyolite-breccia. Its west contact with the granite porphyry is described below under "Structural features."

Granite-porphyry--A body of granite-porphyry forms the walls of the Tunnel from the west portal eastward for about 6100 feet. From the surface geology Vanderwilt and Koschmann (idem, p. 4) concluded that this was the most recent igneous-rock formation in the District. They describe the rock as follows: "The granite-porphyry is gray and consists of phenocrysts of zoned feldspar, abundant quartz, and biotite in a light-gray fine-grained matrix. The chilled facies found near its margins contains a smaller percentage of phenocrysts and has a denser ground-mass than the main mass."

Linear elements of the structure of the granite-porphyry were determined where possible in the Tunnel and are locally well shown by the alinement of schist-inclusions and of phenocrysts. The average dip of the linear elements in the Tunnel indicates that the body came into position very steeply from the south and west, though near the west portal it is essentially structureless.

A few large inclusions of a much coarser porphyritic granite and larger numbers of schist-fragments were found. The larger of the granite-fragments was well rounded and had ghosty outlines grading into the porphyry-mass. Fragments of the more basic schists gave less indication of fluxing with the magma. No fragments of rhyolite were found in the porphyry, and Vanderwilt and Koschmann likewise failed to find rhyolite-inclusions, though diligent search was made for them near contacts with the rhyolite exposed at the surface.

Structural features in the Tunnel

Contact of the granite-porphyry and porphyritic rhyolite--The contact of the granite-porphyry and the porphyritic rhyolite lies about 6100 feet east of the west portal and shows some interesting relations that may have a bearing upon the conditions of intrusion of the granite-porphyry. The contact dips 65°-70° west and the porphyritic rhyolite has a pronounced fluidal texture drawn out in the direction of dip of the contact-plane. Nearest to the granite the rhyolite is dense and cryptocrystalline, but within a few inches to a foot it changes to alternating thin layers of dense rhyolite and fluidal porphyritic rhyolite. Within a few feet the rock grades into normal porphyritic rhyolite, and the platy and linear structures assume a more nearly horizontal position. The general nature of the contact suggests that the rhyolite has been chilled against the granite and is the younger rock, but there are several features which indicate that this conclusion is probably not correct. First, the linear stretching in the rhyolite east of the contact for some distance ranges between 12° and 35° northwest to west, but within the contact-zone it changes abruptly to 65° or 70° south 60° west. Second, the linear stretching corresponds approximately in strike and dip with the linear stretching throughout a long distance in the granite-body west of the contact. Third, the texture in the contact-zone of the rhyolite does not correspond to the chilled margin of the rhyolite at its east contact with the fluidal rhyolite breccia, where there is a few inches of glassy margin only, and pronounced stretching is decidedly absent.

It is probable, therefore, that the granite is the younger rock and has somewhat fused and sheared the rhyolite during its emplacement. The possibility that the granite-porphyry has partly fused the rhyolite may also account for the fact that no inclusions of rhyolite could be found in the granite-porphyry, even though at the surface the rocks are everywhere in contact. Either the fluxing of the rhyolite near the contact inhibited fragmentation, or perhaps fragments actually engulfed were entirely fused or recrystallized by the granite-magma.

Tectonic breccia and rubble--One of the most striking geologic features of the tunnel-section is the brecciation or fragmentation of the pre-Cambrian formations near the channels through which the fluidal rhyolite-breccia and other rhyolite-bodies were erupted. An anomalous feature of the surface-geology was the occurrence of bodies of pre-Cambrian breccia interlayered with and underlying the rhyolite-lavas. The origin of the breccia is of critical importance in explaining its association with the rhyolite. The exposures in the tunnel demonstrate rather conclusively that the breccia is of tectonic origin and not a superficial accumulation of explosive and surface-debris, such as might fill the throat of a volcanic neck.

The occurrences of the breccia lie between points about 8300 and 15,800 feet east of the west portal. In this total distance of 7500 feet, about 3800 feet is composed chiefly of pre-Cambrian rocks, in rubble, fissured and brecciated blocks, or more or less solid bodies. The remainder, about 3700 feet, is composed chiefly of fluidal rhyolite-breccia containing many fragments of the broken rocks. The 3800 feet of broken pre-Cambrian material is also seamed by or engulfed in rhyolite, but is subordinate in amount to the enclosed fragments or blocks.

At several places blocks of pre-Cambrian rocks that had been fractured and seamed with rubble or breccia stringers or that were composed entirely of coarse rubble cemented by ground-up rock particles were found engulfed in the fluidal rhyolite-breccia. Thus aside from the general relations of the rhyolite-intrusions to the zones of brecciation, these occurrences show that brecciation occurred before the eruption of the rhyolite-magma.

In the Tunnel all gradations were seen between solid pre-Cambrian granite or schist, irregularly fractured rock with some stringers of broken material along the fractures, and rock composed of irregular to subrounded fragments enclosed in a matrix of smaller fragments and comminuted rock-material. In these bodies rhyolitic material is entirely absent, but as explained above it may occur cutting through similar broken material in the form of dikes or stringers. It is characteristic of many of the breccia-zones that the pre-Cambrian material composing the fragments is comparatively homogeneous, that is, either entirely granite, entirely schist, or mixtures of granite, schist, and pegmatite associated in the manner found in solid pre-Cambrian rock. This seems to indicate that the breccia was not produced by explosively propelled debris of heterogeneous nature that came to rest at some distance from its source, but rather that the fragmentation was produced by disruption of solid rock in place. Where a great amount of rhyolitic magma has engulfed or penetrated the breccia it may be more heterogeneous, as illustrated in certain parts of the tunnel-section, where most of the larger fragments in the fluidal rhyolite-breccia are granite, though numerous small fragments of schist are suspended in the rhyolite.

The origin of the breccia and rubble thus seems to be related to some mechanical shock that fractured the rock, augmented by some movement incident to the breaking up of such large volumes of the crust. If explosive escape of gases prior to the eruption of the rhyolite had been the cause of the brecciation, the rubble-bodies would have a more heterogeneous composition because of the resulting movement and mixing. Furthermore, exactly comparable phenomena are to be found in the Silverton Quadrangle, near the Red Mountain District. The large fractures and faults that outline the sunken block of the Silverton caldera (W. S. Burbank, Vein-systems of Arrastre Basin, and regional geologic structure in the Silverton and Telluride quadrangles, Colorado, Colo. Sci. Soc. Proc., v. 13, No. 5, 1933) are likewise characterized by wide zones of brecciation and rubble-formation in blocks near the fractures. Zones of breccia and rubble 400 to 500 feet wide occur in the San Juan tuff in this District. This breccia is likewise characterized by the absence of mixing of adjacent rock-formations where these are brecciated in contact.

By analogy, then, it is possible that the brecciation of the pre-Cambrian formations of the Twin Lakes Tunnel has been produced by the opening and closing of large tension-fractures in the Earth's crust, perhaps accompanied by a moderate amount of faulting. The shock produced by the sudden closing of an open fracture would probably be sufficient to disrupt the solid rock for some distance on each side of the main fracture. The probable general course of this zone of fracturing in the Independence Pass Area is considered in the discussion of the correlation of surface-features and tunnel-section.

Faults and fissures--Extending about 2600 feet east of the zone of brecciation and rhyolite-intrusions in the Tunnel is another zone of numerous faults and fissures in the solid pre-Cambrian rocks. A large proportion of the faults have a low-angle westerly dip toward the zone of brecciation, with an upward and eastward or reverse movement of the hanging wall. The amount of displacement may not be large on individual faults, for in many of them the matching of displaced layers of pegmatite and schist shows that the movements were somewhat less than the dimensions of the Tunnel. In certain faults the movement could be established as greater than 8 or 10 feet. There are also many steep faults, some of which have displaced the flat faults, though others appear to be of nearly the same age of movement.

As these faults in general are parallel to the openings and fissures in the zone of brecciation and to the general trend of the zone of breccia-bodies at the surface, it is probable that they are genetically related to the phenomena that caused the brecciation. It is conceivable that closing of large tension-fractures and repeated movements would tend to produce outward thrusting in the shallower walls of the fissure, as the broken material in the brecciated zone would occupy greater space than the original rock.

General conclusions and correlation with surface-geology

If it is assumed tentatively that a large fissure was opened in the Earth's crust and that brecciation was coextensive with this fissure-line, the distribution of the breccia on the surface should give further evidence as to the direction and extent of the fissure. At the southeast corner of the area shown on the map of the Independence Pass District (J. W. Vanderwilt and A. H. Koschmann, op. cit.) this breccia occupies part of a zone 4 to 6 miles wide, but some of the most westerly outcrops are interbedded in the rhyolite and thus probably are not in their original position. The eastern boundary of the rhyolite, together with associated occurrences of breccia, extends from this southeast corner in a nearly straight line about north 30° west to the vicinity of the town of Independence. To the southeast of the limits of this map Vanderwilt and Koschmann (personal communication) have established that the "quartz-hornblende diorite" of the Twin Lakes District (J. V. Howell, op. cit., pp. 53-58, 1919) is identical with the pre-Cambrian breccia of the Independence Area in its structural features, though composed possibly of somewhat different rock. Howell describes the rock as follows: "The diorite is a uniform greenish-gray crystalline rock, occurring as a coarse breccia. The individual fragments of the breccia range in size from a fraction of an inch to many feet in greatest dimension." Howell's cross-section [his Fig. 15a] shows the breccia extending downward as a body below the eastern edge of the Grizzly Peak rhyolite, a relation exactly similar to that encountered in the Twin Lakes Tunnel farther north.

It is probable, therefore, that the eastern limit of the Grizzly Peak rhyolite marks the approximate line of fissuring and brecciation. The eastern boundary of the crustal block involved in the movement may extend then from the vicinity of Independence about south 30° east for at least 10 to 12 miles. The northern boundary is also probably limited by the northern edge of the rhyolite, along which small outcrops of the breccia extend westward from Independence in the direction of the valley of Roaring Fork.

The evidence supplied by the Tunnel and the surface-geology suggests that the mechanics of eruption of the Grizzly Peak rhyolite was about as follows: Movement or pressure of an underlying magma caused the separation of a block of the crust. Surficially the continued movements of this block caused brecciation of its walls, especially along the eastern boundary. Rhyolite magma, having its source from the fissures, was then extravasated by penetration through the brecciated mass to the surface. The surface expression of the fissured zones perhaps consisted only of mounds of the brecciated bed-rock together with a small amount of original surface-debris. If some faulting occurred, an escarpment mantled with the breccia might result. Rhyolite issuing from the fissures and soaking through the breccia could readily cause portions of the material to move small distances as breccia-flows. Large blocks or bodies of the brecciated pre-Cambrian rocks probably would not be carried far by these movements of the rhyolite-magma, though owing to the viscosity of the magma small fragments would be carried great distances. Further geologic mapping of the region should be done to establish the areal limits of the breccia-bodies and the directions of movement of the rhyolite-bodies on the surface. Geomorphic studies are also needed to determine the exact position and nature of the surface at the time of eruption. Until further work of this kind has been done, the conclusions set forth above must be considered tentative.

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PRELIMINARY REPORT ON EQUILIBRIUM-RELATIONS BETWEEN FELDSPATHOIDS, ALKALI-FELDSPARS, AND SILICA

J. F. Schairer and N. L. Bowen

Several years ago, an investigation of phase equilibrium-relations in the system $NaAlSiO_4$-$KAlSiO_4$-SiO_2, was begun. These studies, now well along, throw considerable light on the composition of natural nephelite, on the pseudo-leucite reaction, and on the possible courses of crystallization in alkaline magmas. The system, involving as it does, two common feldspathoids, leucite and nephelite, the alkali feldspars, and the forms of silica, is of great interest to petrologists.

The limiting binary systems

The System, $NaAlSiO_4$-$KAlSiO_4$--This system was studied by Bowen (N. L. Bowen, Amer. J. Sci., v. 43, pp. 115-132, 1917). $NaAlSiO_4$ crystallizes in two forms, nephelite (hexagonal) and car-

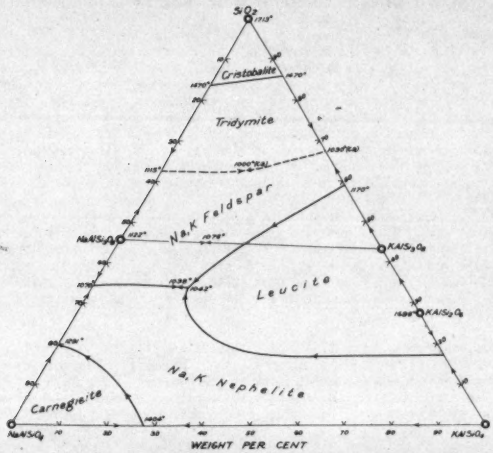

FIG. 1—EQUILIBRIUM-DIAGRAM FOR THE TERNARY SYSTEM, $NaAlSiO_4$–$KAlSiO_4$–SiO_2 (ARROWS INDICATE FALLING TEMPERATURE; PAIRED CONCENTRIC CIRCLES INDICATE THE COMPOSITION OF A COMPOUND)

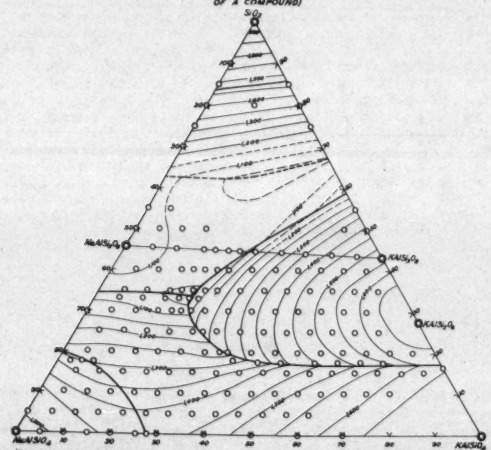

FIG. 2—EQUILIBRIUM-DIAGRAM FOR THE TERNARY SYSTEM, $NaAlSiO_4$–$KAlSiO_4$–SiO_2 WITH ISOTHERMS (ALL DATA IN WEIGHT PER CENT; CIRCLES INDICATE DETERMINED POINTS)

negieite (isometric), the former stable below 1248° C, the latter stable from that temperature to its melting point at 1526° C. $KAlSiO_4$ has two forms, an hexagonal form and an orthorhombic form, the latter apparently stable only at high temperatures. There is a complete series of solid solutions between $NaAlSiO_4$ (nephelite) and $KAlSiO_4$. Carnegieite takes up a limited amount of $KAlSiO_4$ in solid solution. The eutectic between carnegieite solid solution and the hexagonal solid solution is at 1404° C.

The System, $KAlSiO_4$-SiO_2--G. W. Morey and N. L. Bowen (Amer. J. Sci., v. 4, pp. 1-21, 1922) determined that potash-feldspar melts incongruently to leucite and liquid at 1170° C and only becomes completely liquid at 1530° C. N. L. Bowen and J. F. Schairer (Amer. J. Sci., v. 18, pp. 301-312, 1929) determined the melting point of leucite at 1686 ± 5° C. With $KAlSiO_4$ and SiO_2 as components, both leucite and potash-feldspar become binary compounds. The more complete data on this system will be published later.

The System, $NaAlSiO_4$-SiO_2--Greig and Barth (unpublished data) have studied the binary system, $NaAlSiO_4$-$NaAlSi_3O_8$. Both forms of $NaAlSiO_4$, nephelite, and carnegieite, take a limited amount of $NaAlSi_3O_8$ (albite) into solid solution and the inversion-temperature is raised since more albite goes into the nephelite than into the carnegieite.

With $NaAlSiO_4$ and SiO_2 as components albite becomes a binary compound. There is a eutectic between albite and silica.

The Ternary System

The fields of stability at liquidus temperatures in the ternary system, $NaAlSiO_4$-$KAlSiO_4$-SiO_2, are presented in Figure 1. Some of the temperatures may require revision before final publication. No field for orthorhombic $KAlSiO_4$ is shown because precise data are lacking at this time. In the field labelled carnegieite, isometric ternary solid solutions involving the molecules $NaAlSiO_4$, $KAlSiO_4$, and $NaAlSi_3O_8$, are in equilibrium with liquid. In the field labelled Na,K nephelite, hexagonal ternary solid solutions involving these same molecules are in equilibrium with liquid. In the field labelled Na,K feldspar, binary solid solutions involving the molecules $NaAlSi_3O_8$ and $KAlSi_3O_8$ are in equilibrium with liquid.

The ternary diagram with isotherms is given in Figure 2. Open circles represent compositions upon which thermal data have been obtained up to this time. Further work is in progress.

In order to follow the complete course of crystallization of any composition in the ternary system a knowledge of the compositions of the several solid phases in equilibrium with liquid at each temperature is necessary. The composition of the liquid-phase in equilibrium with two solids at any temperature can be read from Figure 2. If one or both of the solid phases be solid solutions (and all our ternary compositions have at least one solid solution in equilibrium with liquid at some temperature), it is necessary to determine the three-phase triangles (for a discussion of three-phase triangles and three-phase boundaries, see N. L. Bowen, J. F. Schairer, and E. Posnjak, Amer. J. Sci., v. 26, pp. 233-239, 1933) for the appropriate temperature.

The coexistence of two solid solution series in rocks is a common occurrence. The coexistence of two binary solid solution series in investigated silicate systems has been described in the system, CaO-FeO-SiO_2 (N. L. Bowen, J. F. Schairer, and E. Posnjak, Amer. J. Sci., v. 26, pp. 193-284, 1933), and the system, MgO-FeO-SiO_2 (N. L. Bowen and J. F. Schairer, Amer. J. Sci., v. 29, pp. 151-217, 1935). In the system, $NaAlSiO_4$-$KAlSiO_4$-SiO_2, two solid solution series may coexist, one of which is binary (the Na,K feldspars), but the other is a ternary solid solution series (the Na,K nephelites). This complicates the determination of three-phase triangles. Much information on three-phase triangles in this system has been obtained but it is not yet complete. Detailed data on the paths of crystallization will be published later.

The composition of nephelite--It is well known that when the chemical analyses of rock-forming nephelites are plotted they show a decided grouping in a small area. This limitation of the composition of nephelites is due to the fact that the natural magmas from which they form tend to have a composition approaching the invariant points at 1042° and 1038° and the nephelite in equilibrium with such liquids is that around which natural nephelites tend to cluster. Only in a few rocks relatively rich in potash do the nephelites rich in potash occur as true rock-forming minerals and then they are likely to reveal a changing composition (zoned structure) which reflects the change of composition of the liquid towards these low-temperature invariant points during crystallization.

On the basis of X-ray measurements of crystal-structure F. A. Bannister (Min. Mag., v. 22, p. 608, 1931) has suggested that no complete series of solid solutions between nephelite and $KAlSiO_4$ could form. If solid solution were only partial there should be in the ternary system a boundary-curve separating the field of nephelite from that of $KAlSiO_4$ and this boundary-curve should mark a discontinuity of some kind in the fusion-surface. No such boundary-curve or discontinuity of the surface is to be found. The results of the ternary system thus confirm the earlier results of the binary system which indicated complete solid solution between $NaAlSiO_4$ and $KAlSiO_4$ as nephelite mix-crystals. Bannister has shown that kaliophilite from Vesuvius has a different structure from natural nephelite mix-crystals. Vesuvian kaliophilite must therefore represent a different hexagonal form of $KAlSiO_4$ from that at the potash-end of the nephelite series.

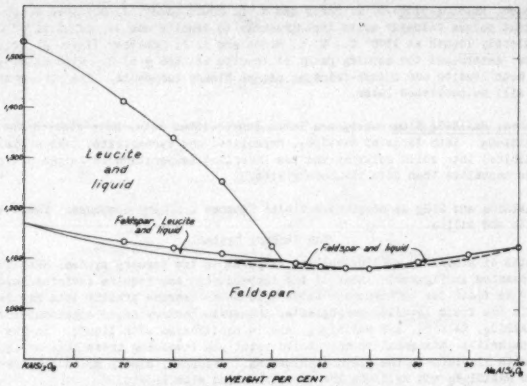

FIG. 3—THE ALKALI FELDSPAR JOIN IN THE TERNARY SYSTEM (CIRCLES INDICATE DETERMINED POINTS)

The pseudo-leucite reaction-point--The invariant point at 1042° where the fields of leucite, alkali feldspar, and nephelite meet is a reaction-point, leucite reacting with liquid to form alkali feldspar and nephelite. The existence of such a point was predicted by N. L. Bowen (The evolution of the igneous rocks, Princeton, 1928, pp. 245-248), who has discussed its importance in connection with the formation of some alkaline rocks.

The alkali feldspars--In Figure 3 we present the feldspar-join in the ternary system. Heavy lines refer to binary equilibrium. All curves that refer to ternary equilibrium are shown as lighter lines. These lighter lines, therefore, give only the temperature at which phase changes occur in a mixture of a given total composition. They do not give the composition of all phases concerned in the equilibrium, since these relations can be shown only with the aid of a ternary diagram. The determined points are represented by open circles. In this diagram we have interpreted the data (admittedly incomplete) as showing a complete series of solid solutions with a minimum between potash-feldspar and albite. The actual data do not necessitate this type of diagram. All that is known is that the temperatures of completion of melting are lower in intermediate mixtures. The temperatures of beginning of melting have not been determined and have been indicated only by a broken curve. It is possible that when these latter temperatures have been determined it will be found that there is really a eutectic between potash and soda-feldspars and therefore an hiatus, presumably of small magnitude, between two series of solid solutions. All petrologists are familiar with the different types of diagram for the alkali-feldspars that various authors have suggested by reasoning from natural rocks. We regret that our results do not as yet enable us to decide between the two alternatives mentioned above. The diagram is given at this time principally to emphasize the wide extension of the leucite field on the alkali feldspar-join. It is necessary for such a feldspar to have more than 53 wt per cent albite in order to eliminate the incongruent melting with formation of leucite.

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THE PRE-CAMBRIAN IGNEOUS ROCKS OF EASTERN PENNSYLVANIA AND MARYLAND

Florence Bascom

The Blue Ridge and Piedmont geomorphic provinces, topographically distinct but geologically a unit, extend southwestward across eastern Pennsylvania and central Maryland, in a belt with an average width in these States of some 50 miles.

In these provinces are exposed the crystalline formations of the Atlantic belt. Gneisses (with sporadic interbedded graphitic schist and marble), quartz-schist, crystalline limestone,

and schists, constitute the pre-Cambrian sedimentary series which has been folded, overturned, and overthrust with faulting, to the northwest.

These formations with the associated intrusives and extrusives are exposed at the surface in the major portion of the Blue Ridge and the Piedmont Upland. Less metamorphosed Cambro-Ordovician sediments with open folds and normal faults, together with unmetamorphosed, gently inclined Triassic sediments overlie and conceal the pre-Cambrian crystalline formations in the Piedmont Lowlands, an inconsiderable portion of the Piedmont province.

Igneous rocks--The pre-Cambrian igneous rocks constitute a petrographic association of plutonics, dikes, and lava-flows. The plutonics range from peridotite to quartz-monzonite, with pyroxenite, anorthosite, olivine gabbro, gabbro, norite, quartz-gabbro, quartz-diorite, and granodiorite as intermediate types. The volcanics range from basalt to quartz-latite, with andesite and dacite as intermediate facies. The dikes include basalt, diabase, pegmatite, and aplite.

A chemical and petrographic examination of this material has been made for the purpose of determining what relationship, if any, exists between the different types of plutonics, between the different types of volcanics, and finally between the plutonics and volcanics; and for the further purpose of determining their possible origin from a common parent magma and the character of the processes which might have produced the successive types.

Age--The time period represented by these rock-types is probably late pre-Cambrian. Older intrusives (early pre-Cambrian) have not been included in this study, and younger (epi-Carboniferous and Triassic) intrusives may be given a separate discussion.

The order of intrusion of the rock-types is thought from field evidence to be: (1) Anorthosite; (2) granite (quartz-monzonite, granodiorite); (3) gabbro (quartz-diorite, diorite, quartz-gabbro, gabbro, norite, olivine-gabbro, olivine-norite); (4) peridotite and pyroxenite; (5) pegmatite; and (6) vein-material of hydrothermal origin.

The order of extrusion is: (1) The silicic lavas (quartz-latite, dacite, rhyo-dacite, latite); and (2) the subsilicic lavas (andesite, basalt).

The order of differentiation, as will be indicated, is thought to be the following: (1) Peridotite; (2) pyroxenite; (3) anorthosite; (4) olivine-gabbro and members of the gabbro-family including quartz-diorite; (5) granodiorite; (6) quartz-monzonite; (7) pegmatite; and (8) aplite and other hydrothermal veins.

In order of areal extent the plutonics may be listed as follows: (1) Granite (circa 513 square miles); (2) gabbro (circa 272 square miles); (3) peridotite, pyroxenite, serpentine (circa 53 square miles); and (4) anorthosite (circa 20 square miles).

The effusives may be listed as follows: (1) Rhyolitic lava (circa 140 square miles); and (2) basaltic lava (circa 190 square miles).

There may be drawn three generalizations similar to those drawn by Daly [3] for North America and Europe, namely: (1) No alkalic rocks; (2) granitic types dominant among the intrusives; and (3) basaltic type dominant among the extrusives.

Pre-Cambrian intrusives and effusives

(1) Peridotite--This type, which crops out in several roughly parallel interrupted belts trending northeast with the strike of the sediments and in numerous small scattered lens-shaped areas, is associated in many places with considerable intrusions of gabbro; it never occurs as perfectly fresh material but is always more or less altered or completely altered by low-temperature hydrothermal action to serpentine and associated minerals, possibly in part deuteric.

Because of the stability under surface-conditions of these alteration products and because of the dominance of magnesia, the topographic expression of this rock-type consists in low and somewhat barren ridges.

A considerable variety of minerals, in addition to or replacing the chief alteration product, serpentine (williamsite, chrysotile, sepiolite, picrolite), develop during hydrothermal alteration of peridotite. Such minerals are deweylite, talc, asbestos, anthophyllite, tremolite, hornblende, actinolite, epidote, zoisite, chlorite, clinochlore, vermiculite, pectolite, magnetite, chromite (also an original constituent), hematite, limonite, calcite, aragonite, magnesite, breunnerite, brucite, quartz, chalcedony, opal, and more rarely zaratite, goethite, and hydromagnesite.

Where peridotite is not completely altered to one or more of these minerals, it is a dark-colored, greenish-brown, coarse-grained rock pitted on weathered surfaces, with serpentinized olivine-crystals in relief and ferromagnesian minerals lining the pits.

Upon microscopic examination the constituents prove to be olivine (about 24 per cent), bronzite, hypersthene, or augite or diallage (about 25 per cent), with actinolite, talc or serpentine as alteration products (about 50 per cent). Where peridotite is completely altered it has become a serpentine rock or a soapstone or with extreme weathering a siliceous iron-stone.

The peridotite is represented by two analyses, No. 82 (cortlandite) and No. 84 (lherzolite) of Table 1, by the two norms Nos. 73 and 83 of Table 2, by a computed average composition (only analyses made in the laboratory of the United States Geological Survey or by Dr. H. S. Washington in the Geophysical Laboratory of the Carnegie Institution of Washington are utilized) and average norm, No. I of Table 3 and No. I of Table 4. These analyses and norms, the average analysis, and norm indicate an extremely femic rock, with the ferromagnesian silicates dominant and about equally divided between pyroxene and olivine. The alkalies are negligible; magnesia is extreme. This is a common type of peridotite.

In the C.I.P.W. classification (W. Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, Quantitative classification of igneous rocks, University of Chicago Press, 1903) they fall in class "IV.1.4.1(2). and "V.(1)2.$_2$ (1)2., that is, the femic constituents are dominant or extreme, the femic silicates extreme or dominant as compared with the iron oxides; in the first type olivine is the dominant silicate and in the second pyroxene is dominant over olivine; in the first-named type again magnesia, iron, and lime are extreme and in the second they are dominant over the alkalies, and finally in both magnesia is dominant over lime.

The average of the peridotite analyses falls in class (IV)V.(1)2.$_{"3}$1".1". and is perfemic, or extremely rich in femic minerals, dopolic, the femic silicates dominant over the iron oxides, pyrolic, pyroxene and olivine equal, permirlic, magnesia, iron and lime extreme as compared with the alkalies, and finally permagnesic or magnesia dominant over iron oxides.

(2) Pyroxenite--This type is intimately associated in character and outcrop with the peridotite, into which it merges and from which it is only distinguished by the absence of olivine. Like the peridotite it also ultimately passes into serpentine through a similar series of alteration-products.

The fresh type may be a diallage-bronzite, a diallage-hypersthene, an augite-hypersthene, or augite-enstatite rock; the altered type may be a tremolite, actinolite or steatite schist, a hornblendite, smaragdite, or tremolite-serpentine, or serpentine rock.

Pyroxenite is represented in Table 1 by analyses numbers 45, 46, 47, 48, 51, 53, 54, 58, and 66, and in Table 2 by norms numbers 74, 76, 77, 78, 79, 80, 81, 82, and 84, and by a computed average composition and norm in Table 3 No. II and in Table 4 No. II.

These nine analyses and norms reveal a rock, like the peridotite, extremely femic, with ferromagnesian silicates not merely dominant, as with the peridotite, but extreme with pyroxene rather than olivine the dominant silicate, with magnesia, iron, and lime dominant over the alkalies, and magnesia dominant but not extreme as in the peridotite.

The classes represented are as follows:

IV(V). 1.$_1$ 1. 1. Minnesotose	"V. 1.$_1$.2". 2. Cecilose
IV". 1.$_1$ 1". (I)2. Cookose	"V. 1.$_{(1)2}$ 2. "2. Baltimorose
"V. 1.$_1$ 1. "2. Maricose	(IV)V. (1)2.$_1$.2. "2. Chesterose
"V. 1.$_1$2". 1(2). Websterose	Norm of average analysis of 5
V. 1.$_1$ 2. 1". Websterose	"V. 1.$_1$ "2. (1)2. Cecilose
"V. 1.$_1$ 2". 2. Cecilose	

(3) Anorthosite--This is not a widespread type. It is exposed in an area approximately 20 square miles (52 square kilometers) in extent, located about 40 miles northwest of Philadelphia. It is essentially a labradorite or andesine-labradorite rock, with small and scanty grains of apatite, magnetite, and biotite as accessory constituents [12].

Zoisite is the dominant alteration-product and the source of the characteristic blue color of the rock. Sericite, clinozoisite, epidote, actinolite, calcite, and leucoxene are other secondary constituents.

Table 1--Composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland

Rock-type	Aplite	Grano-diorite	Grano-diorite	Quartz-latite	Rhyo-da-cite	Quartz-latite	Quartz-latite	Dacite	Quartz-mon-zonite	Aporhy-olite	Quartz-mon-zonite	Grano-diorite
Column	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12
Compound												
SiO_2	99.32	79.27	77.94	77.20	76.07	76.02	75.96	75.72	74.95	74.30	74.41	76.86
Al_2O_3	0.11	9.44	9.92	10.66	11.59	11.23	11.41	12.29	14.29	12.34	11.50	12.92
Fe_2O_3	0.21	1.76	1.84	2.85	2.40	1.97	3.10	0.85	trace	2.10	2.85	1.02
FeO	0.12	1.48	1.77	0.39	0.30	1.36	0.40	2.60	0.51	4.06	.....	2.59
MgO	0.03	0.76	0.94	trace	0.06	0.00	0.14	0.37	0.16	0.26	0.78	0.50
CaO	0.05	0.72	1.67	0.08	0.54	0.58	trace	2.65	0.48	0.34	1.64	3.75
Na_2O	0.03	1.82	2.72	3.29	5.48	2.80	2.73	3.63	3.06	3.60	2.09	2.82
K_2O	0.06	1.53	1.34	4.67	2.74	4.95	5.51	0.78	5.37	2.60	4.09	1.48
H_2O+	0.05	1.65	0.95	0.13	0.38	0.22	0.00	0.29	0.66	0.40	0.75	1.06
H_2O-	0.02			0.06	0.10	0.37	0.20	0.12	0.26			
TiO_2	0.00	0.71	0.70	0.22	0.25	0.30	0.30	0.29	0.05	.....	1.82	.....
ZrO_2	n.d.	.....	.....	.....	.....	.....	.....	0.00	.....	.....	.....	.....
CO_2	.....	.....	.....	0.12	trace	0.00	0.14	trace	.....	.....	.....	.....
P_2O_5	0.00	0.19	0.11	trace	trace	trace	0.10	0.05	0.21	.....	0.07	.....
SO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
F	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	n.d.	.....	.....	.....	.....	.....	.....	0.11	.....	.....	.....	.....
Cr_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
V_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
NiO	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
MnO	0.00	0.67	0.08	0.33	trace	0.20	0.01	0.18	trace	.....	.....	.....
BaO	n.d.	.....	0.02	.....	0.09	.....	.....	0.07	.....	.....	.....	.....
SrO	.....	.....	.....	.....	.....	.....	.....	trace	.....	.....	.....	.....
Li_2O	.....	trace	.....	.....	.....	.....	.....	0.00	trace	.....	.....	.....
FeS_2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Misc.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 1--Composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Rock-type	Quartz-mon-zonite	Quartz-latite	Grano-diorite	Quartz-mon-zonite	Quartz-mon-zonite	Quartz-mon-zonite	Quartz-mon-zonite	Grano-diorite	Grano-diorite	Grano-diorite	Grano-diorite	Grano-diorite
Column	No.13	No.14	No.15	No.16	No.17	No.18	No.19	No.20	No.21	No.22	No.23	No.24
Compound												
SiO_2	73.62	73.60	72.60	71.67	71.49	71.35	71.13	70.68	70.27	70.08	69.61	68.72
Al_2O_3	12.81	13.10	15.12	14.97	14.38	13.13	13.87	15.35	15.94	13.92	14.39	14.78
Fe_2O_3	0.65	3.26	0.59	0.77	2.07	1.80	1.33	0.87	0.75	1.05	.....	1.28
FeO	1.55	0.36	1.02	1.12	2.78	1.99	1.91	1.37	1.83	3.07	3.61	2.62
MgO	0.12	0.32	0.30	0.51	1.17	1.12	1.28	0.52	0.77	1.26	2.45	2.05
CaO	1.08	0.82	1.65	2.50	1.58	1.44	1.14	3.43	2.59	3.09	3.22	3.34
Na_2O	2.47	2.28	3.92	3.08	1.95	3.78	3.37	4.53	3.82	3.26	2.71	3.26
K_2O	6.22	5.40	4.33	4.74	3.28	4.50	3.91	1.59	3.58	2.69	2.68	3.00
H_2O+	0.68	0.71	0.47	0.64	1.30	0.10	0.80	0.51		0.48	0.23	0.27
H_2O-	0.14					0.08	0.33	0.37	0.45	0.19		
TiO_2	0.17	.....	.....	.....	.....	0.36	0.79	0.32	.....	0.52	.....	0.42
ZrO_2	.....	.....	.....	.....	.....	.....	.....	0.03	.....	trace	.....	.....
CO_2	0.38	.....	.....	.....	.....	.....	.....	0.24	.....	0.11	.....	.....
P_2O_5	0.04	0.06	.....	.....	.....	0.23	0.14	0.11	.....	0.10	.....	0.14
SO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
F	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	.....	.....	.....	.....	.....	0.04	.....	trace	.....	0.09	.....	.....
Cr_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
V_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
NiO	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
MnO	0.03	0.09	.....	.....	.....	0.08	.....	0.02	.....	trace	.....	0.12
BaO	0.04	.....	.....	.....	.....	.....	.....	0.03	.....	0.09	.....	.....
SrO	.....	.....	.....	.....	.....	.....	.....	.....	.....	trace	0.10	.....
Li_2O	.....	.....	.....	.....	.....	.....	.....	0.03	trace	trace	.....	.....
FeS_2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Misc.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 1--Composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Rock-type	Quartz-diorite	Grano-diorite	Quartz-monzonite	Grano-diorite	Quartz-monzonite	Quartz-diorite	Quartz-diorite	Quartz-monzonite	Grano-diorite	Ande-site	Grano-diorite	Quartz-gabbro
Column	No.25	No.26	No.27	No.28	No.29	No.30	No.31	No.32	No.33	No.34	No.35	No.36
Compound												
SiO_2	68.72	67.36	67.13	66.47	64.50	64.44	64.22	63.35	63.34	62.87	62.82	62.05
Al_2O_3	14.97	14.20	15.32	14.87	15.89	17.34	15.87	16.67	17.95	18.15	19.10	11.95
Fe_2O_3	0.74	1.33	2.77	1.58	1.14	0.59	2.74	3.35	1.48	3.15	0.98	1.89
FeO	2.79	3.23	3.40	3.31	4.84	3.72	1.44	3.86	1.93	1.75	3.20	1.39
MgO	1.62	2.85	1.65	2.18	0.23	1.40	2.80	2.33	1.21	0.33	1.69	1.78
CaO	2.84	3.71	1.36	4.88	2.11	5.53	7.43	0.80	3.43	0.69	4.27	11.43
Na_2O	4.89	2.87	2.00	2.84	4.37	4.22	3.43	2.38	5.31	6.46	3.93	1.25
K_2O	0.89	2.84	3.25	2.04	6.04	1.05	0.77	3.22	4.91	5.46	3.38	2.55
H_2O+	0.07	0.69	1.68	0.16	0.43	0.53	0.50	2.67	.....	0.85	0.63	2.41
H_2O-	1.75		0.29	1.09	0.04	0.37	0.15	0.23	.....	0.05		
TiO_2	0.26	0.47	0.84	0.50	0.42	0.46	0.45	0.91	0.44	0.10	.....	1.00
ZrO_2	trace	0.00	.....	.....	trace	trace	0.02	.....	.....	.....	.....	.....
CO_2	trace	.....	.....	.....	.....	trace	.....	.....	.....	trace	.....	.....
P_2O_5	0.24	0.31	0.14	0.10	trace	0.23	0.16	0.11	.....	0.06	.....	0.20
SO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.00	.....	.....
F	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	0.08	0.02	.....	.....	0.06	trace	trace	.....	.....	.....	.....	.....
Cr_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
V_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
NiO	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
MnO	0.12	0.08	0.13	0.10	0.03	0.07	0.02	0.09	.....	0.08	.....	.....
BaO	0.02	0.04	0.04	0.08	0.10	0.03	0.00	0.03	.....	trace	.....	.....
SrO	.....	.....	trace	trace	.....	0.02	.....	trace	.....	trace	.....	.....
Li_2O	.....	.....	.....	trace	.....	.....	.....	trace	.....	.....	.....	trace
FeS_2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	2.10[a]
Misc.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[a] Fe_2S_8

Table 1--Composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Rock-type	Quartz-gabbro	Quartz-diorite	Quartz-gabbro	Quartz-monzonite	Quartz-gabbro	Quartz-gabbro	Quartz-gabbro	Gabbro	Web-sterite	Pyrox-enite	Pyrox-enite	Web-sterite
Column	No.37	No.38	No.39	No.40	No.41	No.42	No.43	No.44	No.45	No.46	No.47	No.48
Compound												
SiO_2	58.53	57.61	56.38	56.12	56.09	55.91	55.07	53.91	53.72	53.23	53.00	52.98
Al_2O_3	16.09	14.47	15.18	25.20	14.73	15.59	17.48	16.67	1.31	5.32	3.13	1.93
Fe_2O_3	2.89	5.55	1.60	3.08	2.11	1.21	2.61	1.37	1.40	1.17	.....	1.43
FeO	6.11	6.50	6.24	5.12	6.97	6.27	5.82	7.68	3.88	4.67	7.91	7.89
MgO	2.33	4.48	7.17	1.11	8.10	6.82	4.34	5.64	22.48	28.92	20.00	20.68
CaO	7.38	4.21	6.76	0.19	7.96	7.30	8.48	8.82	15.40	0.60	14.38	13.06
Na_2O	2.11	3.23	2.21	1.03	1.62	2.23	1.83	2.98	.....	0.13	trace	0.11
K_2O	1.01	0.21	1.34	4.59	0.80	1.25	1.08	0.67	.....	0.04	trace	0.07
H_2O+	1.27	0.83	2.00	2.08	1.37	1.85	2.01	0.53	0.83	4.03	0.98	0.86
H_2O-	0.21		0.08			0.18	0.18	0.14	0.09			0.14
TiO_2	1.41	2.01	0.69	0.95	.....	1.11	0.64	0.84	0.15	0.09	0.00	0.26
ZrO_2	0.09	.....	0.14	.....	.....	.....	0.02	.....	.....	.....	.....	trace
CO_2	0.37	.....	.....	.....	.....	.....	0.00	0.40	.....	.....	.....	0.10
P_2O_5	.....	0.33	0.05	.....	0.08	0.16	0.21	0.13	trace	0.26	.....	trace
SO_3	.....	.....	.....	0.34	.....	.....	.....	.....	.....	.....	.....	.....
F	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	.....	.....	.....	.....	.....	.....	.....	0.09	.....	.....	(0.26)	.....
Cr_2O_3	.....	.....	0.05	.....	.....	0.04	.....	trace	0.53	1.31	0.23	0.20
V_2O_3	0.02	.....	.....	.....	.....	.....	0.04	.....	.....	.....	trace	0.03
NiO	.....	.....	.....	.....	.....	.....	0.01	trace	.....	.....	.....	0.03
MnO	.....	0.57	0.11	.....	0.17	0.08	0.15	0.13	0.21	0.23	0.11	0.22
BaO	0.18	.....	.....	.....	.....	.....	trace	trace	.....	.....	.....	.....
SrO	.....	.....	.....	.....	.....	.....	trace	trace	.....	.....	.....	0.00
Li_2O	.....	.....	.....	.....	.....	.....	trace	trace	.....	.....	.....	0.00
FeS_2	.....	.....	.....	0.02	.....	.....	.....	.....	.....	.....	.....	.....
Misc.	.....	.....	.....	0.17	.....	.....	0.03	.....	.....	.....	.....	0.03
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 1--Composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Rock-type	Anorthosite	Gabbro	Websterite	Olivine gabbro	Pyroxenite	Pyroxenite	Andesite	Olivine gabbro	Gabbro	Pyroxenite	Gabbro	Gabbro
Column	No.49	No.50	No.51	No.52	No.53	No.54	No.55	No.56	No.57	No.58	No.59	No.60
Compound												
SiO_2	52.72	52.33	52.28	52.05	51.90	50.78	50.50	50.46	50.05	50.03	49.93	49.79
Al_2O_3	26.61	11.92	2.70	16.27	2.53	3.40	17.42	15.71	15.09	2.00	12.58	14.55
Fe_2O_3	1.03	4.14	1.26	0.46	2.88	1.39	8.15	2.12	3.38	2.38	1.98	5.98
FeO	0.74	12.20	4.87	9.00	9.37	8.11	4.34	7.46	8.31	8.67	10.26	9.12
MgO	0.38	2.77	20.28	5.73	25.95	22.76	3.58	7.59	5.43	26.81	5.58	5.10
CaO	10.90	5.81	16.44	9.43	3.60	12.31	4.30	9.39	10.34	5.05	10.62	10.26
Na_2O	4.43	4.84	0.27	1.84	0.00	trace	4.75	3.78	3.01	0.00	2.72	1.24
K_2O	0.92	1.50		3.18	0.00	trace	0.08	0.96	0.65	0.00	0.59	0.31
H_2O+	1.48				2.82		2.74					
H_2O-	0.11	0.68	1.08	0.98	.....	0.52	0.16	0.86	1.40	4.15	1.25	0.63
TiO_2	0.25	2.86	0.14	trace	0.00	.....	3.11	1.33	2.10	0.00	3.95	2.80
ZrO_2	trace	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
CO_2	trace	.....	.....	.....	.....	.....	trace	.....	.....	.....	.....	.....
P_2O_5	0.33	0.76	trace	0.73	.....	trace	0.63	0.20	0.09	.....	trace	0.22
SO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
F	.....	.....	.....	.....	0.79	trace	.....	.....	.....	.....	.....	.....
S	0.05	.....	.....		0.16	0.24	.....	.....	.....	0.26	.....	.....
Cr_2O_3	.....	.....	0.44	.....	0.60	0.32	.....	.....	.....	.....	.....	.....
V_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.36	.....	.....
NiO	.....	.....	.....	trace	.....	.....	.....	.....	.....	.....	.....	.....
MnO	0.02	trace	0.24	0.33	.....	0.17	0.24	0.14	trace	0.29	0.24	trace
BaO	0.03	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
SrO	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Li_2O	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
FeS_2	.....	.....	.....	.....	.....	.....	.....	.....	0.15	.....	0.30	.....
Misc.	.....	0.19[a]	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[a] CuO

Table 1--Composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Rock-type	Gabbro	Gabbro	Gabbro	Olivine gabbro	Gabbro	Pyroxenite	Norite	Olivine gabbro	Gabbro	Gabbro-diorite	Gabbro-diorite	Olivine gabbro
Column	No.61	No.62	No.63	No.64	No.65	No.66	No.67	No.68	No.69	No.70	No.71	No.72
Compound												
SiO_2	49.65	49.62	48.85	48.83	48.59	48.41	48.03	47.94	47.69	47.68	47.64	46.73
Al_2O_3	17.74	18.17	12.05	8.79	14.36	2.65	20.02	16.62	17.78	13.77	17.36	15.75
Fe_2O_3	3.46	0.33	7.11	1.04	3.99	6.70	1.13	2.94	2.50	4.37	1.79	3.05
FeO	7.57	12.82	9.53	9.50	10.07	6.85	7.29	9.08	11.05	11.10	7.77	10.56
MgO	6.07	2.12	5.35	15.16	6.31	19.35	10.05	8.20	5.34	5.57	10.13	8.19
CaO	8.58	9.69	9.49	14.67	9.21	10.25	11.42	9.36	9.16	10.33	13.06	7.48
Na_2O	2.37	2.74	1.20	0.64	2.31	0.20	0.51	2.21	2.49	3.05	1.47	3.71
K_2O	0.50	0.34	0.91	0.10	0.47	0.06	0.05	0.40	0.72	0.52		0.57
H_2O+	1.36	0.74	1.07	0.52	2.03	3.26	0.57	1.51	0.96	0.84	0.78	0.30
H_2O-		0.15		0.07	0.46	0.25	0.10					
TiO_2	1.74	2.01	3.51	0.37	1.69	0.57	0.23	1.00	2.00	2.36	.....	2.84
ZrO_2	.....	trace	.....	.....	.....	0.00	.....	.....	.....	.....	.....	.....
CO_2	.....	0.00	.....	.....	0.00	trace	0.25	0.57	trace	.....	.....	.....
P_2O_5	0.57	0.58	0.38	.....	0.29	0.75	trace	0.17	0.12	0.41	.....	0.47
SO_3	.....	.....	.....	.....	.....	0.00	.....	.....	.....	.....	.....	.....
F	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	.....	.....	.....	.....	trace	0.00	0.00	.....	.....	.....	.....	.....
Cr_2O_3	.....	.....	.....	0.15	trace	0.46	0.03	.....	.....	.....	.....	.....
V_2O_3	.....	.....	.....	.....	.....	.....	0.02	.....	.....	.....	.....	.....
NiO	.....	.....	.....	.....	trace	0.05	0.01	.....	trace	.....	.....	.....
MnO	trace	0.37	0.55	0.16	0.22	0.19	0.18	.....	0.19	.....	.....	0.35
BaO	.....	.....	.....	.....	trace	0.00	0.00	.....	.....	.....	.....	.....
SrO	.....	.....	.....	.....	0.00	.....	0.00	.....	.....	.....	.....	.....
Li_2O	.....	.....	.....	.....	trace	.....	.....	.....	.....	.....	.....	.....
FeS_2	0.39	0.32	.....	.....	.....	.....	0.11	.....	.....	.....	.....	.....
Misc.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 1--Composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Concluded

Rock-type	Olivine gabbro	Hypersthene gabbro	Basalt	Gabbro-diorite	Gabbro	Hypersthene gabbro	Hypersthene gabbro	Norite	Gabbro	Lherzolite	Gabbro	Cortlandtite
Column	No.73	No.74	No.75	No.76	No.77	No.78	No.79	No.80	No.81	No.82	No.83	No.84
Compound												
SiO_2	46.72	46.67	46.60	46.46	46.34	45.35	45.33	44.63	43.86	43.60	43.24	39.14
Al_2O_3	19.96	17.12	14.16	19.56	15.28	16.11	23.01	18.76	19.93	1.69	22.29	4.59
Fe_2O_3	2.30	2.18	5.08	3.19	1.98	3.42	1.51	2.18	4.20	8.84	0.81	3.45
FeO	4.60	7.60	9.39	7.92	10.15	3.50	8.33	4.72	8.57	2.59	9.22	6.14
MgO	10.13	10.34	5.83	7.69	12.06	12.32	5.88	11.29	4.99	27.15	5.73	31.60
CaO	13.79	13.46	10.10	12.99	8.86	18.04	12.50	14.54	11.63	6.25	13.30	3.23
Na_2O	1.32	1.75	2.37	1.55	0.33	.....	0.76	0.89	1.23	0.50	1.24	0.42
K_2O	trace	.....	0.77	0.09	0.25	1.26	0.32	0.11	0.15	.....	1.13	0.14
H_2O+	0.88	0.88	2.97	1.55	4.01	.....	1.52	2.35	1.89	1.08	1.54	9.36
H_2O-			0.54					0.17	0.11	7.60	0.09	0.50
TiO_2	0.30	.....	1.66	.....	0.71	.....	0.62	0.13	2.23	0.12	1.25	0.52
ZrO_2	.....	.....	.....	.....	.....	.....	.....	.....	0.10	.....	.....	.....
CO_2	.....	.....	0.00	.....	.....	.....	.....	.....	0.00	.....	.....	.....
P_2O_5	trace	.....	0.35	.....	0.10	.....	0.13	0.00	0.52	trace	0.10	trace
SO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
F	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Cr_2O_3	.....	.....	.....	.....	.....	.....	.....	0.08	0.00	0.44	trace	0.41
V_2O_3	.....	.....	.....	.....	.....	.....	.....	.....	0.05	.....	.....	.....
NiO	.....	.....	.....	.....	trace	.....	.....	.....	0.01	.....	.....	0.30
MnO	trace	.....	0.18	.....	0.43	.....	0.09	0.15	0.28	0.19	0.06	0.20
BaO	.....	.....	.....	.....	.....	.....	.....	.....	0.00	.....	.....	.....
SrO	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Li_2O	.....	.....	.....	.....	.....	.....	.....	.....	trace	.....	trace	trace
FeS_2	.....	.....	.....	.....	.....	.....	.....	.....	0.25	.....	.....	.....
Misc.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

The anorthosite has not been found in exposures and the study of it is therefore limited to boulders.

Analysis No.49 of Table 1 and norm 31 of Table 2 represent the anorthosite, also No. V of Table 3 and No. IX of Table 4 labradorose. I.5.'4. (4)5. The norm shows a rock extremely rich in salic constituents, prevailingly a soda-lime feldspar, labradorite, ($Ab_1An_{1.16}$).

(4) Gabbro--The gabbro-family (olivine-gabbro, hypersthene-gabbro, gabbro-norite, gabbro-diorite, diorite, quartz-gabbro, and quartz-diorite) of plutonics intrusive in the crystalline formations from eastern New York to Virginia is one of the more important igneous types of eastern Pennsylvania (Delaware) and Maryland. It is associated with the Baltimore gneiss in large intrusive masses and in many smaller scattered intrusions.

The gabbro is a medium-grained bronze-gray or green-gray rock, depending upon the freshness of the ferromagnesian constituents. The more abundant type is a hypersthene-augite-plagioclase (labradorite, labradorite-bytownite, bytownite) rock with olivine or quartz as variable constituents. Accessory constituents are biotite, hornblende, magnetite, apatite, titanite, pyrite, pyrrhotite, garnet, and zircon. Deuteric and secondary minerals are zoisite, epidote, actinolite, chlorite, and serpentine.

The periodotite and the pyroxenite pass into olivine-gabbro and gabbro with an increase in accessory feldspar (bytownite), and gabbro with an increase in silica merges into quartz-diorite, granodiorite, and quartz-monzonite. Associations and petrographic constitution alike indicate a common ancestral magma.

The chemical characters of the gabbro, quartz-gabbro, diorite, and quartz-diorite are shown in numbers 25, 30, 31, 36, 37, 38, 39, 41, 42, 43, 44, 50, 52, 56, 57, 59, 60, 61, 62, 63, 64, 65, 67, 68, 69, 70, 71, 72, 73, 74, 76, 77, 78, 79, 80, 81, and 83 in Table 1 and by norms 21, 26, 35, 38, 39, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 64, 65, 66, 67, 68, 69, 70, 71, 72, and 75 in Table 2. The average composition and the norm of the average of the gabbroitic rocks are shown in Table 3 by numbers III, IV, VI, VII, and XII, and Table 4 by numbers III, IV, V, VI, and XIII. An inspection of the average analyses and norms of olivine-gabbro (2), gabbro (7), quartz-gabbro (5), and quartz-diorite (3), from

Table 2--Norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland

Classification	I.1. 3.2.	I.2. 2.4.	I.3.1.3.				I.3. 1.4	I.3.2.3.			I.3. 2.4.	I.3. 3.4.
Name	Victorare	Schuylkillose	Alaskose				Tordrillose	Tehamose			Alsbachose	Susquehannose
Rock-type and description	Aplite, River Road Maryland	Granodiorite, Overbrook Pa.	Quartz-latite, Fairfield Quad, Pa.	Quartz-latite, Carlisle Quad, Pa.	Quartz-monzon. Brookville, Md.	Quartz-latite, Fairfield Quad, Md.	Quartz-latite, South Mountain, Pa.	Quartz-latite, Fairfield Quad, Pa.	Quartz-monzonite, Frankford, Pa.	Quartz-monzon. Sykesville, Md.	Granodiorite Great Falls, Md.	Granodiorite, Port Deposit, Md.
	I.1. (2)3.2".	I.2. "2.(3)4.	I.3". 1."3.	I.3". 1.3.	I.3(4). 1.3	I.3(4). 1".3.	I(II).3. 1".".4.	I.3(4). (1)2. (2)3.	I".3. 2."3.	I(II).3. 2.3.	I."3. 2".4.	I".3. 3.4
Column	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12
Mineral												
Quartz	98.88	60.42	38.52	39.96	35.40	37.62	39.30	37.50	41.64	41.10	53.52	41.22
Orthoclase	0.56	8.90	32.80	27.80	31.69	29.47	15.01	32.25	23.91	19.46	7.78	8.90
Albite	.....	15.20	23.06	27.77	25.88	26.20	30.39	19.39	17.29	16.24	23.06	23.58
Anorthite	.....	2.78	.....	0.28	1.67	1.95	1.67	3.89	8.06	7.78	7.51	18.07
Corundum	.....	3.88	0.92	.....	2.86	.....	2.96	2.04	0.61	4.69	1.33	.....
Nethe-line	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Diopside	0.35	.....	.....	.....	.....	0.75	.....	.....	.....	.....	.....	0.48
Hyper-sthene	.....	3.35	0.40	.....	1.19	0.40	6.38	0.90	2.51	6.33	0.86	5.02
Olivine	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Magne-tite	0.23	2.55	0.46	1.82	.....	2.78	3.02	1.39	.....	3.02	2.53	1.39
Ilmenite	.....	1.37	0.61	0.46	0.15	0.61	.....	.....	.....	.....	1.44	.....
Chromite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Apatite	.....	0.34	.....	.....	0.34	.....	.....	.....	.....	.....	0.34	.....
Hema-tite	.....	.....	2.72	1.76	.....	.....	.....	2.24	2.82	.....	.....	.....
Pyrite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Water	0.07	1.66	0.20	0.19	0.92	0.59	0.40	0.71	0.74	1.30	0.96	1.06
Misc.	0.03	.....	0.25	0.12	.....	.....	.....	0.06	1.87	.....	0.10	.....
Total	100.12	100.45	99.94	99.96	99.90	100.37	99.13	100.37	99.45	99.92	99.42	99.72

analyses made in the chemical laboratory of the United States Geological Survey, reveals a gradation from about equal amounts of salic and femic constituents to a dominance of the salic minerals, from extreme excess of feldspar to equal amounts of quartz and feldspar, and from dominance of lime over alkalies to about equal amounts of lime and alkalies with soda extreme to dominant. The norm of the average of three analyses of quartz diorite is (I)II. 4.3. 4(5)., Tonalose, and is dominantly salic, with feldspar dominant over quartz, equal amounts of lime and alkalies, and soda dominant over potash.

The norm of the average of five quartz-gabbro analyses is II.4.4.4., Bandose, differing from the preceding only in the dominance of lime over the alkalies as is to be expected from the character of the feldspar.

The norm of the average of seven analyses of gabbro is (II)III.5.4."4(5). Auvergnose, differing from the quartz-gabbro only in that feldspar is extreme of the salic minerals.

The norm of the average of two olivine-gabbro-analyses is III".5.(4)5.5. Kedabekose, in which the femic minerals slightly exceed the salic, with feldspar extreme over quartz and lime extreme over the alkalies.

The gabbro-family is thus seen to range from a salfemic (salic and femic constituents equal), perfelic (feldspar exceeding the quartz), and percalcic (lime exceeding the alkalies) magma to a magma in which the salic constituents are dominant (dosalic), quartz dominant over feldspar (quardofelic), and alkalies and lime equal (alkali-calcic), with soda always the dominant alkali, that is, from a typical subsilicic magma to one that approaches a silicic magma, an intermediate type. The norm of

Table 2--Norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Classification	I.3. 3.5.	I.4. 1.4.	I.4.2.3.						I.4. 2.5.	I.4.3.3.		I.4. 3.4.
Name	Vulcanose	Kallerudose	Toscanose						Marisposose	Amiatose		Yellowstonose
Rock-type and description	Dacite, South Port Deposit, Md. I".3. "3.(4)5.	Rhyodacite, Fairfield Quad, Pa. I.(3)4. 1.4.	Quartz-monzonite, Rodman St., D.C. I".(3)4. "2.3".	Quartz-monzon. Boyertown Quad, Pa. I."4. (1)2. (2)3.	Quartz-monzonite, River Rd., D.C. I".4. (1)2.3.	Quartz-monzo. Woodstock, Md. I.4. 2.3.	Q.-m.to g.-d., Guilford, Md. I.4. 2.3".	Granodiorite, Dorsey Run, Md. I.4. 2".3(4).	Quartz-diorite, Aldham Station, Pa. I(bI). "4.2". (4)5.	Granodiorite, Newark Street, D.C. I(II).4. (2)3. 3(4).	Granodiorite, Broad Branch, D.C. I(II). (3)4."3. 3(4).	Granodiorite, Boyertown Quad, Pa. I."4. (2)3.4.
Column	No.13	No.14	No.15	No.16	No.17	No.18	No.19	No.20	No.21	No.22	No.23	No.24
Mineral												
Quartz	43.98	33.54	32.16	31.98	27.78	28.68	28.68	26.88	27.30	27.12	30.30	29.64
Orthoclase	4.45	16.12	23.35	36.70	26.69	28.36	25.58	21.13	5.56	17.79	15.57	9.45
Albite	30.39	44.54 (ac)	28.82	20.96	31.96	26.20	33.01	31.96	41.39	27.77	23.06	38.25
Anorthite	13.07	1.85	5.00	5.56	5.56	12.51	8.34	12.79	12.51	15.85	15.01	16.68
Corundum	0.82	.....	2.24	.....	.....	0.10	0.92	1.22	1.43	0.41	1.43	.....
Nethe-line	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Diopside	.....	0.43 (Wol)	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Hypersthene	4.73	1.04	4.26	2.01	4.57	2.62	2.12	4.67	8.32	8.50	12.70	2.49
Olivine	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Magnetite	1.16	0.23	1.86	0.93	2.55	1.16	0.93	1.16	1.16	1.86	.....	1.39
Ilmenite	0.61	0.46	1.52	0.46	0.61	.....	.....	.....	0.46	0.76	.....	0.61
Chromite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Apatite	.....	.....	0.34	.....	0.67	.....	.....	.....	0.67	0.34	0.34	0.34
Hematite	.....	1.60	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pyrite	0.12	.....	.....	.....	.....	.....	.....	.....	0.12	.....	.....	.....
Water	0.41	0.49	1.13	0.82	0.18	0.64	0.47	0.45	1.83	0.27	1.22	0.88
Misc.	0.12	.....	.....	0.49	0.12	.....	.....	.....	0.02	.....	.....	0.24
Total	99.86	100.30	100.68	99.91	100.69	100.27	100.05	100.26	100.77	100.67	99.63	99.97

the gabbro-family calculated from the average of these analyses falls into class II(III).4(5). 4.4(5). Bandose, a quartz-gabbro closely approaching the gabbro.

In general the gabbroic intrusives strike with the formations which they invade and dip with the schistosity. They vary greatly in width of exposure and are seldom exposed continuously for long distances but rather occur as a series of lenses, associated with other intrusives or penetrating the gneisses in many parallel almost paper-thin injections.

(5 and 6) Granite (granodiorite and quartz-monzonite)--The granitic rocks have been referred to more than one period of intrusion [10], the early pre-Cambrian, later pre-Cambrian, and epi-Carboniferous.

The early pre-Cambrian, with few exposures (Maryland) and not represented by an analysis, is not included in this study.

The epi-Carboniferous, or Woodstock, Dorsey Run, and Ellicott City granite of Baltimore County, and the Guilford granite of Howard County are relatively unaltered binary granites with but slight deformation, with their greatest extent normal to the strike of the sedimentary formations and to the pre-Cambrian intrusives. Their norms have been listed with the other intrusives but they have not been utilized in the calculation of a parent magma.

The main body of pre-Cambrian granite, more or less deformed, extends interruptedly from Georgia through Pennsylvania and northward roughly parallel to the fall line and the strike of the sedimentaries. This granite ranges in lime-soda feldspar-content from more than 55 per cent (55.62) to less than 10 per cent (9.21) and in potash-feldspar from less than 8 per cent (7.78) te more than 30 per cent (36.70); that is, it ranges from a typical granodiorite (biotite-granite)

Table 2--Norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Classification	I.4.3.4.			I.5. 1.4.	I.5.2.3.		I.5. 4.5.	II.3. 1.2.	II.3.2.3.		II.4.3.3.	
Name	Yellowstonose			Nordmarkose	Pulaskose		Labradorose	Varingase	Hispanare		Harzose	
Rock-type and description	Quartz-diorite, Reading Quad., Pa. I.4. 3.4(5).	Granodiorite, Philadelphia, Pa. I(II).3 (4).(2) 3.(3)4.	Granodiorite, Dorsey Run, Md. I(II).4 (5)."3. (3)4.	Latite, Boyertown Quad., Pa. I.5. 1.(3)4.	Quartz-monzonite, Phoenixville Quad, Pa. I(II).4 (5).(1) 2.3.	Quartz-diorite, Norristown Quad, Pa. I.(II). "5.2. 3(4).	Anorthosite, Honeybrook Quad, Pa. I.5. "4.(4)5.	Quartz-monzonite, Pennsylvania (I)II.3" 1.2.	(Q.-m.) g.-d., Chain Bridge, D.C. I(II).3. 2.3".	(Q.-m.) g.-d., Cabin John Br., D.C. II.3". (1)2.3.	Quartz-gabbro, Burlington Quad, Pa. II.(3)4. 3.4."3.	Granodiorite, Tilden Street, D.C. (I)II.4. "3.3(4).
Column	No.25	No.26	No.27	No.28	No.29	No.30	No.31	No.32	No.33	No.34	No.35	No.36
Mineral												
Quartz	20.22	30.72	13.38	2.16	8.70	5.40	0.54	28.32	36.78	31.32	26.52	26.40
Orthoclase	6.12	16.12	20.02	32.80	36.14	28.91	5.56	27.24	19.46	18.90	15.01	16.68
Albite	35.63	27.77	33.01	55.02	37.20	45.06	37.73	8.38	16.77	19.91	10.48	24.63
Anorthite	25.30	14.46	21.13	3.61	5.56	10.56	50.04	0.83	5.84	3.06	19.74	16.68
Corundum	.....	0.20	1.22	0.20	.....	.....	.....	18.26	6.32	8.16	.....	0.20
Nepheline	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Diopside	0.92	.....	.....	.....	4.40	5.16	1.97	.....	.....	.....	19.70	.....
Hypersthene	8.58	7.16	9.22	1.20	5.15	2.09	0.20	8.08	7.00	8.84	.....	11.19
Olivine	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Magnetite	0.93	1.39	1.39	4.64	1.62	2.09	1.39	4.41	3.94	4.87	2.78	1.86
Ilmenite	0.91	0.91	.....	0.15	0.76	0.76	0.46	1.82	1.52	1.67	1.52	0.91
Chromite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Apatite	0.34	0.34	.....	.....	.....	.....	0.67	.....	0.34	0.34	0.34	0.67
Hematite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pyrite	.....	.....	.....	.....	0.12	.....	.....	.....	.....	.....	2.13	.....
Water	0.90	0.67	0.63	0.91	0.47	.....	1.60	2.08	1.97	2.90	2.43	0.69
Misc.	0.05	0.96	.....	0.14	0.13	.....	0.10	0.53	0.04	0.03	.....	0.14
Total	99.90	100.70	100.00	100.83	100.25	100.03	100.26	99.95	99.98	100.00	100.65	100.05

in the District of Columbia, at Port Deposit, and northeast into Pennsylvania, to a quartz-monzonite (binary granite) also found in the District of Columbia, northwest of the granodiorite, and extending through Montgomery and Carroll counties, Maryland, and into Pennsylvania northwest of the granodiorite.

Quartz is a constant constituent of both types, ranging around 30 per cent; feldspar averaging about 65 per cent varies from orthoclase, microcline, and oligoclase in the southern end of the belt of intrusives to microcline and microperthite in the extreme northern end.

Augite, hypersthene, or hornblende or biotite averaging about 7 per cent are ferromagnesian constituents associated with the usual accessory minerals.

The granodiorite is typically a biotite-granite; biotite is the prevailing ferromagnesian constituent; either hornblende or muscovite may occur as accessory minerals but do not play the role of chief constituents. In Pennsylvania the rock has a porphyritic texture which becomes increasingly conspicuous to the northeast.

Analyses of the granodiorite are listed in Table 1, numbers 2, 3, 12, 20, 22, 23, 24, 26, 28, and 33. The corresponding norms are numbers 2, 10, 12, 22, 23, 24, 25, 30, 36, and 37 of Table 2. The average of the analyses and the norm of the average are shown in Tables 3 and 4 under numbers VIII and VII.

The average of five of the superior analyses of the granodiorite discloses a rock in which the salic minerals have reached extreme dominance; quartz and feldspar are present in about equal

Table 2--Norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Classification	II.4.3.4.		II.4.3.5.		II.4.4.4.				II.5.4.3.-5.			
Name	Tonalose		Placerose		Bandose				Hessose			
Rock-type and description	Granodiorite, Port Deposit (R), Md. (I)II."4.3."4.	Quartz-diorite, Phoenixville Quad, Pa. "II.4. 3(4). 4(5).	Quartz-diorite, Delaware R., Pa. II.4. 3.5.	Andesite, Fairfield Quad, Pa. II.4(5). 3.5.	Quartz-gabbro, Georgetown, D.C. II".4". "4.4.	Quartz-gabbro, Stoney Run, Md. II.4. 4.4.	Quartz-gabbro, Porters' Bridge, Md. II.4. 4.4.	Quartz-gabbro, Tri-delphia, Md. II".4". "4.4.	Gabbro, Ilchester, Md. II."5. 4(5). 3(4).	Gabbro, Radnor, Pa. II(III)."5."4. 4(5).	Gabbro, Fountaine, Pa. II(III). 5.4."5.	Gabbro, Burlington Quad, Pa. II(III). "5.4. (4)5.
Column	No.37	No.38	No.39	No.40	No.41	No.42	No.43	No.44	No.45	No.46	No.47	No.48
Mineral												
Quartz	28.14	24.00	21.06	9.48	10.62	21.60	13.50	10.26	.....	4.63	2.70	5.10
Orthoclase	12.23	4.45	1.11	0.56	7.78	6.12	6.67	7.23	6.67	3.89	2.22	2.78
Albite	22.53	28.82	27.25	39.82	18.34	17.82	15.20	18.86	5.24	25.15	23.06	19.91
Anorthite	22.52	25.85	19.18	18.07	27.80	31.41	36.42	28.91	51.99	30.30	36.14	36.70
Corundum	.....	.....	.....	2.86	.....	.....	.....	.....	.....	.....	.....	.....
Netheline	.....	.....	.....	.....	.....	.....	.....	.....	2.84	.....	.....	.....
Diopside	0.89	7.99	.....	.....	4.73	2.32	4.08	5.16	11.01	10.44	7.44	2.26
Hypersthene	9.16	3.30	16.35	8.90	24.72	11.50	16.70	23.32	.....	20.50	21.40	22.29
Olivine	.....	.....	.....	.....	.....	.....	.....	.....	17.10	.....	.....	.....
Magnetite	2.32	3.25	7.89	5.57	2.32	4.18	3.71	1.86	1.16	2.09	0.46	5.10
Ilmenite	0.91	0.91	3.80	5.93	1.37	2.74	1.22	2.13	2.43	1.67	3.80	3.34
Chromite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Apatite	0.34	0.34	0.67	1.34	0.10	1.01	0.34	0.34	0.34	0.34	1.34	1.34
Hematite	.....	0.48	.....	4.32	.....	.....	.....	.....	.....	.....	.....	.....
Pyrite	.....	.....	.....	.....	.....	.....	0.03	.....	.....	0.18	0.60	0.39
Water	1.25	0.65	0.83	2.89	2.05	1.48	2.19	2.03	1.63	0.67	0.89	1.37
Misc.	.....	0.04	.....	.....	0.19	0.11	0.05	0.04	.....	0.40	.....	.....
Total	100.29	100.08	99.98	99.74	100.05	100.29	100.11	100.14	100.41	100.26	100.05	100.58

amounts as are also the alkalies and lime, and of the alkalies soda is still dominant. The rock-type is I(II).4. (2)3."4. Yellowstonose.

Classification of norms of the granodiorite are as follows:

I. 2. "2. (3)4. Schuylkillose
I. "3. 2". 4. Alsbachose
I". 3. 3. 4. Susquehannose
I(II). (3)4. "3. 3(4). Amiatose
I(II). 4. (2)3. 3(4).
I. "4. (2)3. 4. Yellowstonose
I(II). (3)4. (2)3. (3)4.
I(II). 4(5). "3. (3)4.
I(II). "5. 2. 3(4). Pulaskose
I(II). 4. "3. 3(4). Harzose
(I)II. "4. 3. "4. Tonalose
Norm of average analysis (5)
I(II). 4. (2)3. "4. Yellowstonose

The quartz-monzonitic type is usually a binary granite of a light-gray color with a foliated texture due largely to the arrangement of the mica.

The analyses of the quartz-monzonite are given in Table 1 by numbers 9, 11, 13, 17, 18, 19, 27, 29, 32, and 40. The corresponding norms are numbers 5, 8, 9, 15, 16, 17, 29, 32, 33, and 34 of Table 2. The average of eight superior analyses of quartz-monzonite and the norm of the average are shown in Tables 3 and 4 by numbers IX and VIII.

It will be noted that the quartz-monzonite and the granodiorite are closely related in chemical and mineral constitution. The norm of the average in both types shows salic constituents extremely dominant, quartz and feldspar present in about equal amounts with a difference in the feldspar. In the quartz-monzonite the alkalies are dominant, in the granodiorite alkalies and lime are equal in amount; soda is dominant while in the quartz-monzonite potash is equal to the soda.

Table 2--Norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Classification	II.5.5.1.-5.		III.4.4.4.			III.5. 2.3.	III.5. 2.4.	III.5. 3.3.	III.5. 3.4.	III.5.3.5.		III.5. 4.4.-5.
Name	Corsose		Koghose			Lamarose	Kilanose	Kentallenose	Camptonose	Ornose		Auvergnose
Rock-type and description	Gabbro, Stone Run, Md. II(III).5.(4)5.(4)5.	Gabbro, Hartford County, Md. II*.5.(4)5.4.	Quartz-gabbro, Ridley Creek, Pa. III*.4.4*.4(5).	Quartz-gabbro, Rock Creek, D.C. (II)III.4.4.4.	Quartz-gabbro, Burlington Quad, Pa. III.4.4.(3)4.	Gabbro, Burlington Quad, Pa. II(III).5.2.3*.	Gabbro, South Radnor Station, Pa. *III.5.2.4*.	Quartz-gabbro, Burlington Quad, Pa. (II)III.5.3(4).3.	Quartz-gabbro, Delaware R., Pa. (II)III.5.3.4(5).	Quartz-gabbro, Burlington Quad, Pa. *III.5.3*.(4)5.	Quartz-gabbro, West Chester Quad, Pa. III.5.3*.(4)5.	Quartz-gabbro, Baltimore Co. Md. (II)III.5.4(5).5.
Column	No.49	No.50	No.51	No.52	No.53	No.54	No.55	No.56	No.57	No.58	No.59	No.60
Mineral												
Quartz	2.10	.....	12.78	11.64	12.36	.....	1.08	.....	.....	.....	.....	.....
Orthoclase	1.11	1.67	1.67	5.00	5.56	3.89	8.90	18.90	5.56	3.34	2.78	0.56
Albite	10.48	8.29	10.48	13.62	9.96	20.96	41.39	15.72	31.96	31.34	26.20	13.10
Anorthite	48.37	58.65	33.36	30.58	24.74	35.31	6.39	26.69	23.35	24.19	22.24	46.43
Corundum	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Nepheline	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Diopside	5.23	2.29	13.76	5.19	16.16	7.61	16.49	13.67	18.24	7.48	21.77	15.14
Hypersthene	19.18	24.05	13.25	29.13	12.32	18.93	12.67	16.74	14.75	0.76	9.82	10.56
Olivine	.....	2.00	.....	.....	.....	4.06	.....	5.61	.....	20.89	4.51	9.82
Magnetite	6.03	2.09	5.32	3.02	10.21	3.71	6.03	0.70	3.02	4.41	6.26	4.64
Ilmenite	4.26	1.22	8.82	.....	6.69	3.80	5.47	.....	2.43	5.32	4.56	.....
Chromite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Zircon	0.18	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Apatite	1.34	0.34	0.34	.....	1.01	0.34	1.68	1.68	0.34	1.34	1.01	.....
Hematite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pyrite	0.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Water	2.01	1.52	0.63	1.37	1.07	0.96	0.68	0.99	0.86	0.30	0.84	0.56
Misc.	0.06	.....	.....	0.08	.....	.....	0.19	.....	.....	.....	.....	.....
Total	100.60	100.12	100.41	99.63	100.08	99.57	100.97	100.70	100.51	99.37	99.99	100.81

This reflects the increase in the quartz-monzonite of the potash (orthoclase) feldspar relative to the soda-lime feldspar (plagioclase).

Classification of the norms of quartz-monzonite are as follows:

I. 3(4). 1. 3. Alaskose
I*. 3. 2. *3. } Tehamose
I(II). 3. 2. 3. }
I. *4. (1)2. (2)3. } Toscanose
I*. 4. (1)2. 3. }
I*. (3)4. *2. 3*. }
I(II). (4)5. (1)2. 3. Pulaskose

(I)II. 3*. 1. 2. Varingose
[Inferior analysis, omitted in average]
(I)II. 3.2.3. } Hispanose
*II. 3. (1)2. 3. }
Average of 8 superior analyses
I*. (3)4. *2. 3. Toscanose

As will be noted, the plutonics range from an extremely femic constitution (peridotite and pyroxenite) through a dominant femic character to equal amounts of salic and femic contents (gabbro-family), to dominant and finally extreme salic content (granite-family), and from an excess (peridotite and pyroxenite) of pyroxene and olivine through a dominance of these constituents (gabbro-family) to their considerable replacement by equal amounts of quartz and feldspar (granite-family). Magnesia and lime dominate in the peridotite and pyroxenite; lime is dominant in the gabbro; in the granodiorite it is equaled by the alkalies and in the quartz-monzonite is excelled by the alkalies.

The persistent soda-potash relationship has been noted; wherever both alkalies are present soda is dominant or in the extreme silicic type equals the potash.

Table 2--Norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Continued

Classification	III.5.4.4.-5.							III.5.5.0.				
Name	Auvergnose							Kedabekose				
Rock-type and description	Gabbro, Germantown Quad, Pa. "III.5.(3)4.4(5).	Quartz-gabbro, Burlington Quad, Pa. "III.5.4.(4)5.	Basalt, Fairfield Quad, Pa. III.5."4.4".	Gabbro, Norristown Quad, Pa. III.5.4.(4)5.	Gabbro, Germantown Quad, Pa. III.5.(3)4.(4)5.	Quartz, gabbro, Windsor Rd., Bal. Co., Md. III.5.4".5.	Quartz, gabbro, Baltimore Co., Md. III.5.4(5).	Quartz-gabbro, Pikesville, Pa. (II)III.5.(4)5.5".	Norite, McKinley's Mill, Md. III.5.5.(4)5.	Quartz-norite, Wetheredville, Md. III.5."5."5.	Gabbro, Neshaminy County, Pa. III.5.5.3(4).	Gabbro, Gwynn's Falls, Md. III.5.5.1.
Column	No.61	No.62	No.63	No.64	No.65	No.66	No.67	No.68	No.69	No.70	No.71	No.72
Mineral												
Quartz	1.56	.....	0.42	2.82	2.70	.....	.....	.....	0.60	.....	.....	.....
Orthoclase	3.89	2.22	4.45	2.78	3.34	.....	.....	.....	0.56	0.56	1.67	7.23
Albite	25.15	18.34	19.91	19.39	23.06	14.67	12.58	11.00	4.19	7.34	2.62	.....
Anorthite	25.85	34.47	25.85	27.52	20.29	38.92	41.14	48.65	51.99	46.98	39.48	40.31
Corundum	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Nepheline	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Diopside	20.28	8.80	18.64	13.44	26.47	22.43	19.56	15.90	3.83	20.11	2.69	38.65
Hypersthene	12.75	23.58	16.21	22.00	11.98	1.06	11.63	9.85	35.65	3.03	45.50	.....
Olivine	.....	3.70	.....	.....	.....	18.85	12.47	10.05	.....	15.03	0.31	4.95
Magnetite	4.87	4.18	7.42	5.80	2.78	3.25	2.55	3.25	1.62	3.25	2.09	4.87
Ilmenite	3.95	1.98	3.19	3.19	7.45	.....	.....	0.61	0.46	0.30	1.37	.....
Chromite	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.08	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Apatite	.....	0.34	0.69	0.67	.....	.....	.....	.....	.....	.....	0.34	.....
Hematite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pyrite	0.15	.....	.....	.....	0.30	.....	.....	.....	0.11	.....	.....	.....
Water	1.40	1.50	3.52	2.49	1.25	0.88	0.79	0.88	0.67	2.53	4.01	3.93
Misc.	.....	0.57	.....	.....	.....	.....	.....	.....	0.31	.....	.....	.....
Total	99.85	99.68	100.30	100.10	99.62	100.06	100.72	100.19	99.99	99.21	100.08	99.94

(7) Pegmatite--This type occurring as dikes is for the most part coarse-grained and light-colored and less commonly fine-grained aplites; they are associated with the silicic and the ultra subsilicic plutonics; their constituents are quartz, alkalic feldspar (orthoclase, microcline, microperthite, albite, or oligoclase) and muscovite or biotite, with a considerable list of accessory minerals which includes garnet, tourmaline, pyrite, and corundum.

Unfortunately only one analysis of this material is available; an aplite listed as number I in Table 1 and the norm as number I in Table 2; also number X of Tables 3 and 4. The norm falls in I. 1. (2) 3. 2". No representatives listed. This aplite is described by Washington [13] as occurring in small stringers and veinlets in quartz-monzonite of the River Road Quarry. The mode as described by Washington and the norm are in agreement and show that the rock is almost wholly composed of quartz (98 per cent) with scanty orthoclase (0.56 per cent), and rare muscovite-flakes. The aplite illustrates a late differentiation type with potash dominant and quartz extreme.

(8) Aplite and other hydrothermal veins--The final product of differentiation is represented by the albitites, or hydrothermal veins, with their remarkable reaction-zones, notably those of Brandywine, Brinton's, and Corundum Hill quarries in Pennsylvania.

Pre-Cambrian effusives--These rocks are represented by two types, a silicic and a subsilicic type, with some intermediate facies. They are both widespread formations in South Mountain, Pennsylvania, and the subsilicic type occurs to a less extent in Maryland where it is highly altered and interbedded with pre-Cambrian sediments.

(9) Metabasalts--The original constituents of these effusives were feldspar (orthoclase and plagioclase) augite, olivine, magnetite, or ilmenite. The present character of the rock is de-

Table 2--Norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Concluded

Classification	IV.1.1.1.		IV.1.1.2.		V.1_1.1.2.	V.1_1.2.1.		V.1_1.2.2.		V.1_2.2.2.	V.2_2.2.1.	V.2_1.2.2.
Name	Minnesotose		Cookose		Maricase	Websterose		Cecilose		Baltimorose	Permagnesic	Chesterose
	Pyroxenite, S.of Radnor Sta., Pa. IV(V).1.1.1.	Cortlandite, Howard County, Md. "IV.1.1(2).	Quartz-gabbro, Baltimore Co, Md. IV.1_2.1_2.2.	Pyroxenite, Baltimore Co. Md. IV".1_1.1".(1)2.	Pyroxenite, Johnnycake Rd, Md. "V.1_1.1."2.	Websterite, Baltimore Co, Md. V.1_1.2.1".	Websterite, Baltimore Co, Md. "V.1_1.2.1(2).	Pyroxenite, Dogwood Rd, Md. "V.1_1.2."2.	Websterite, Cecil County, Md. "V.1_1.2."2.	Pyroxenite, Johnnycake Rd, Md. "V.$1_{(1)2}$.2."2.	Lherzolite, Baltimore Co, Md. "V.(1)2_2.(1)$_2$.1.	Pyroxenite, Honeybrook Quad, Pa. "V.(1)2_2.(1)2.1.
Column	No.73	No.74	No.75	No.76	No.77	No.78	No.79	No.80	No.81	No.82	No.83	No.84
Mineral												
Quartz	5.10	.....	.....	.....	1.20	.....	.....	.....	.....	.....	.....	3.66
Orthoclase	.....	1.11	0.56	.....	.....	.....	.....	.....	0.56	.....	.....	0.56
Albite	1.57	3.14	5.24	.....	.....	.....	2.10	.....	1.05	.....	4.19	1.57
Anorthite	1.39	10.29	20.85	5.56	6.95	3.61	6.12	8.62	4.45	9.17	2.22	6.12
Corundum	4.49	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Nethe-line	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Diopside	.....	4.35	41.83	15.44	8.61	57.64	59.87	50.10	48.24	41.32	22.46	32.17
Hypersthene	78.17	15.45	14.66	62.82	75.06	35.17	23.64	38.08	41.95	34.43	33.90	39.82
Olivine	.....	49.14	13.83	7.90	.....	.....	4.85	1.98	0.31	11.83	16.80	.....
Magnetite	1.86	5.10	1.62	3.48	4.18	2.09	1.86	.....	2.09	2.09	8.35	9.74
Ilmenite	0.15	1.06	0.76	.....	.....	0.30	0.30	.....	0.46	.....	0.15	1.06
Chromite	2.02	0.67	0.22	0.67	0.90	0.67	0.67	0.22	.....	0.45	0.67	0.67
Zircon	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.68
Apatite	0.67	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Hematite	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	3.20	.....
Pyrite	.....	.....	.....	.....	.....	.....	.....	.....	0.03	.....	.....	.....
Water	3.99	9.88	0.59	4.16	2.82	0.92	1.09	0.98	1.01	0.52	8.72	3.53
Misc.	0.04	.....	.....	.....	0.35	.....	.....	0.26	0.36	0.24	.....	.....
Total	99.45	100.19	100.16	100.03	100.07	100.40	100.50	100.24	100.51	100.05	100.66	100.58

termined, however, by the secondary constituents, of which epidote and quartz are the most abundant in the massive type. These two minerals not only replace the original constituents but fill the vesicles and cement the cracks. Where the rock has been subjected to stress the dominant alteration-products are actinolite and chlorite. Hematite is an abundant pigment and amphibole-asbestos is in some places associated with quartz as cementing material. Native copper and its compounds more rarely form the amygdules and fill the cracks.

Numbers 55 and 75 of Table 1 show the chemical character of the two prevailing types. Number 55 represents the massive type with a trachytic fabric and with andesine as a still unaltered constituent. In the absence of olivine, the rock may be considered an andesite. The other constituents are magnetite, ilmenite, quartz, and chlorite, and epidote, alteration-products of the pyroxene. Number 75 represents the schistose type in which the original fabric has been obliterated and actinolite, chlorite, and epidote are the prevailing constituents with ilmenite, magnetite, and finely granular feldspar and apatite, as accessory constituents.

The norms appear under numbers 40 and 63 in Table 2. The massive type is plainly more andesitic than the schistose type. The average composition and its norm appear as number XIII in Table 3 and as number XI in Table 4.

II. 4 (5). 3. 5. Placerose III. 5. "4. 4". Auvergnose
Average II". "5. 3(4). "5. Beerbachose

The average basalt ranges from nearly equal amounts to a dominance of the salic constituents over the femic, with feldspar extreme or dominant over the quartz. The lime (feldspathic)

Table 3--Average composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland

Rock-type	Peridotite	Pyroxenite	Olivine-gabbro	Gabbro	Anorthosite	Quartz-gabbro	Quartz-diorite	Granodiorite
Number of specimens	(2)	(5)	(2)	(7)	(1)	(5)	(3)	(5)
Column	No. I	No. II	No. III	No. IV	No. V	No. VI	No. VII	No. VIII
Compound								
SiO_2	41.37	51.40	47.77	47.41	52.72	56.40	65.79	67.32
Al_2O_3	3.11	2.08	14.37	18.60	26.61	15.81	16.06	15.43
Fe_2O_3	6.15	2.96	1.67	2.00	1.03	2.08	1.36	1.31
FeO	4.36	7.33	7.05	8.62	0.74	6.28	2.65	2.49
MgO	29.38	23.05	12.64	6.59	0.38	5.75	1.94	1.76
CaO	4.74	9.47	14.23	11.23	10.90	7.58	5.27	3.76
Na_2O	0.46	0.06	0.98	1.70	4.43	2.00	4.18	3.72
K_2O	0.07	0.03	0.05	0.42	0.92	1.10	0.90	2.88
H_2O+	5.22	2.38	0.70	1.38	1.48	1.68	0.93	0.47
H_2O-	4.05	0.10	0.03	0.17	0.11	0.15	0.19	0.15
TiO_2	0.32	0.20	0.33	1.20	0.25	0.77	0.39	0.43
ZrO_2	.....	.....	.....	0.01	.....	0.05	0.01	0.005
CO_2	.....	0.02	.....	0.09	.....	.....	.....	0.05
P_2O_5	.....	0.15	.....	0.23	0.33	0.17	0.21	0.13
SO_3	.....	0.04	.....	.....	.....	.....	.....	.....
Cl	.....	0.08	.....	.....	.....	.....	.....	.....
S	.....	.....	.....	0.06	0.05	.....	0.02	.....
Cr_2O_3	0.42	0.43	0.07	0.02	.....	0.02	.....	.....
V_2O_3	.....	0.01	.....	0.01	.....	0.01	.....	.....
NiO	0.15	0.02	.....	0.01	.....	.....	.....	.....
MnO	0.20	0.18	0.08	0.20	0.02	0.14	0.07	0.06
BaO	.....	.....	.....	.....	0.03	.....	0.02	0.03
SrO	.....	.....	.....	.....	.....	.....	0.01	0.005
FeS_2	.....	0.01	.....	0.05	.....	0.01	.....	.....
Total	100.00	100.00	99.97	100.00	100.00	100.00	100.00	100.00

Table 3--Average composition, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Concluded

Rock-type	Quartz-Monzonite	Aplite	Average plutonics	Average gabbro	Basalt	Rhyolite	Average volcanics	Volcanics and plutonics
Number of specimens	(8)	(1)	(9)	(4)	(2)	(6)	(2)	(2)
Column	No. IX	No. X	No. XI	No. XII	No. XIII	No. XIV	No. XV	No. XVI
Compound								
SiO_2	69.69	99.32	54.77	54.34	48.55	75.76	62.16	58.46
Al_2O_3	14.54	0.11	18.44	16.21	15.79	11.71	13.75	16.10
Fe_2O_3	1.66	0.21	1.90	1.78	6.62	2.40	4.51	3.21
FeO	2.58	0.12	2.66	6.15	6.87	0.90	3.88	3.27
MgO	1.01	0.03	6.38	6.73	4.71	0.15	2.43	4.41
CaO	1.25	0.05	8.33	9.58	7.20	0.78	3.99	6.16
Na_2O	2.92	0.03	3.15	2.22	3.56	3.37	3.47	3.31
K_2O	4.47	0.06	1.27	0.62	0.42	4.01	2.22	1.74
H_2O+	1.03	0.05	1.77	1.17	2.85	0.29	1.57	1.67
H_2O-	0.18	0.02	0.52	0.14	0.35	0.14	0.24	0.38
TiO_2	0.44	.....	0.33	0.67	2.38	0.23	1.30	0.82
ZrO_2	.....	.....	0.01	0.02	.....	.....	.....	0.01
CO_2	0.05	.....	0.03	0.02	.....	0.04	0.02	0.02
P_2O_5	0.11	.....	0.22	0.15	0.49	0.04	0.27	0.24
SO_3	.....	.....	0.01	.....	.....	.....	.....	0.01
Cl	.....	.....	0.01	0.02	.....	0.02	0.01	0.01
S	0.01	.....	0.01	0.03	.....	.....	.....	.....
Cr_2O_3	.....	.....	0.09	.....	.....	.....	.....	0.04
V_2O_3	.....	.....	0.02	0.01	.....	.....	.....	0.01
NiO	.....	.....	.....	.....	.....	.....	.....	.....
MnO	0.04	.....	0.07	0.12	0.21	0.14	0.17	0.12
BaO	0.02	.....	0.01	0.01	.....	0.02	0.01	0.01
SrO	.....	.....	.....	.....	.....	.....	.....	.....
FeS_2	.....	.....	.....	0.01	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 4--Average norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland

Classification	(IV)V.(1)2. "3.1".1".	"V.1."2. (1)2.	III".5. (4)5.5.	(II)III.5. 4".4(5).	II.4.4.4.	(I)II.4. 3.4(5).	(I)II.4. (2)3."4.	I".(3)4. "2.3.
Name	....	Cecilose	Kedabekose	Auvergnose	Bandose	Tonolose	Yellowstonose	Tokanose
Number of analyses	(2)	(5)	(2)	(7)	(5)	(3)	(5)	(8)
Rock-type	Peridotite	Pyroxenite	Olivine gabbro	Gabbro	Quartz-gabbro	Quartz-diorite	Granodiorite	Quartz-monzonite
Column	No. I	No. II	No. III	No. IV	No. V	No. VI	No. VII	No. VIII
Mineral								
Quartz	.....	0.48	.....	.....	13.38	23.40	23.16	30.33
Orthoclase	.....	.....	.....	2.22	6.67	5.56	17.24	26.69
Albite	3.67	0.52	7.86	14.15	16.77	35.11	31.44	24.63
Anorthite	6.39	5.28	35.03	41.98	30.86	22.24	16.68	5.56
	.....	.....	.....	.....	.....	.....	.....	(c)2.75
Diopside	13.24	32.55	28.51	9.64	4.73	2.51	0.89	.....
Hypersthene	26.79	52.78	13.23	24.26	20.82	6.84	6.87	5.27
Olivine	30.34	.....	11.35	.....	.....	.....	.....	.....
Magnetite	8.82	4.41	2.55	3.02	3.02	2.09	1.86	2.32
Ilmenite	0.61	0.46	0.61	2.28	1.52	0.76	0.76	0.76
Chromite	0.67	0.67	.....	.....	.....	.....	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....
Apatite	.....	0.34	.....	0.67	0.34	0.34	0.34	0.34
Hematite	.....	.....	.....	.....	.....	.....	.....	.....
Pyrite	.....	.....	.....	.....	.....	.....	.....	.....
Water	9.27	2.48	0.73	1.55	1.83	1.12	0.62	1.21
Misc.	0.07	0.13	0.12	0.25	0.09	0.06	0.15	0.12
Total	99.87	100.10	99.99	100.02	100.03	100.03	100.01	99.98

Table 4--Average norms, pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland--Concluded

Classification	I.5. "4.(4)5.	I.1. (2)3.2".	II".5. (3)4."5.	I.3". (1)2.3.	II(III).(4)5. 4.4(5).	"II.4. "3.4.	II."5. (3)4.4.	II.4".3.4.
Name	Labradorose	.....	Beerbachose	Tehamose	Hessose	Tonalose	Hessose	Tonalose
Number of analyses	(1)	(1)	(2)	(6)	(4)	...	...	...
Rock-type	Anorthose	Aplite	Basalt	Rhyolite	Average gabbro	Average B.and R.	Average plutonic	Average plutonic and volcanic
Column	No. IX	No. X	No. XI	No. XII	No.XIII	No. XIV	No. XV	No. XVI
Mineral								
Quartz	0.54	98.88	5.04	38.38	7.86	22.18	4.82	13.26
Orthoclase	5.56	0.56	2.22	23.91	3.34	12.79	7.78	10.56
Albite	37.73	.....	29.87	28.30	18.86	29.34	26.72	27.77
Anorthite	50.04	.....	16.13	3.89	32.53	15.57	31.97	23.91
	.....	.....	.....	(c)0.41	.....	.....	.....	.....
Diopside	1.94	0.35	5.78	.....	11.50	1.98	6.61	4.64
Hypersthene	0.23	.....	12.60	0.40	20.30	6.73	15.68	11.12
Olivine	.....	.....	.....	.....	.....	.....	.....	.....
Magnetite	1.39	0.23	9.51	2.55	2.55	6.50	2.78	4.64
Ilmenite	0.46	.....	4.56	0.46	1.22	2.43	0.61	1.52
Chromite	.....	.....	.....	.....	.....	.....	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....
Apatite	0.67	.....	1.01	.....	0.34	0.67	0.34	0.34
Hematite	.....	.....	.....	0.64	.....	.....	.....	.....
Pyrite	.....	.....	.....	.....	.....	.....	.....	.....
Water	1.60	0.07	3.21	0.43	1.31	1.81	2.29	2.05
Misc.	0.10	0.03	.....	0.13	0.12	0.04	0.10	0.11
Total	100.26	100.12	99.93	99.50	99.93	100.04	99.70	99.92

content slightly dominates or is equal to the alkalies; of the alkalies soda is extreme as in the plutonics, where it is extreme to dominant.

The average of the two analyses, an andesitic basalt, shows dominant salic constituents, extreme feldspar, equal lime and alkalies, with soda extreme.

(10) Aporhyolite-quartz and feldspar--These are the dominant and usually the only primary constituents of this effusive. Biotite is rarely present in small amounts; magnetite and ilmenite are the only accessory minerals; hematite, leucoxene, kaolin, sericite-quartz, epidote, and chlorite are secondary constituents.

The chemical composition of the rhyolite and closely-related types is shown in numbers 4, 5, 6, 7, 8, 10, 14, and 34 of Table 1 and the norms in numbers 3, 4, 6, 7, 8, 13, 14, and 28 of Table 2.

The average composition of 7 aporhyolites and the norm of the average appear as numbers XIV and XII in Tables 3 and 4.

I. 3". 1. "3. Alaskose	I". 3. "3. (4)5. Volcanose
I. 3". 1. 3.	I. (3)4. 1. 4. Kallerudose
I. 3(4). 1". 3.	I. 5. 1(3). 4. Nordmarkose
I(II). 3. 1". "4. Tordrillose	Average of 6 superior analyses
I. 3(4). (1)2. (2)3. Tehamose	I. 3". 1(2). 3. Alaskose

It will be noted that the aporhyolites are without exception extremely rich in the salic minerals, with about equal amounts of quartz and feldspar; the alkalies are extreme or dominant over lime (feldspathic); and soda is dominant or equal to the potash.

The average of 6 superior analyses (persalic, quarfelic, peralkalic, and sodipotassic) shows equal soda and potash.

It is not without significance that the average quartz-monzonite falls in the same class and subrang as the average aporhyolite and is closely related in order and rang.

As to the order the two types are respectively quardofelic (quartz dominant) and quarfelic (quartz and feldspar equal) but approach respectively very closely the quarfelic and the quardofelic. In the rang they are respectively domalkalcic (alkalies dominant over lime) and peralkalcic (alkalies extreme) approaching respectively the peralkalcic and the domalkalcic.

Table 2, which groups the norms of these intrusive and effusive rocks, reveals a striking gradation from a persilicic, perquaric, alkalicalcic, perpotassic magma to a perfemic, dofelic, domeric, domagnesic magma. In this continuous series there seem to be five centers of crystallization: (1) The alaskose-family (I.3.1.3.) which contains three silicic lavas and one silicic quartz-monzonite; (2) the toscanose-family (I.4.2.3.) containing five quartz-monzonites; (3) the yellowstonose-family (I.4.3.4.) containing four granodiorites; (4) the bandose-family (II.4.4.4.) containing four quartz-gabbros; (5) the hessose-family (II.5.4.3+5.) with typical gabbros (4); (6) the auvergnose-family (III.5.4.5.) of seven subsilicic gabbros and olivine-gabbros and one basalt; and finally (7) the kedabekose-family (III.5.5.0.) containing five still more calcic gabbros and olivine-gabbros.

The pyroxenites and peridotites, owing to minor differences in the relative amounts of ferromagnesian constituents, are distributed in eight families and two classes (class II analyses).

Thirty-one analyses fall in class I, ranging from order 1 to 5, with every order represented. Nineteen fall in class II, orders 3 to 5 being represented.

That orders 1 and 2 are rare types everywhere is indicated by the paucity (2) or complete lack (1) of representatives listed in United States Geological Survey Professional Paper 99 (none in order 1, and four in order 2, from Transvaal, Siberia, Antarctica, and California.)

Twenty-two norms fall in class III representing orders 4 and 5; again there are no representatives of orders 1 and 2 listed and only two (Ireland) in order 3.

This distribution of types is due, of course, to the fact that extreme or dominant quartz accompanies rocks rich in salic minerals and that quartz is neither extreme nor dominant nor

even equal to the feldspar in rocks characterized by equal proportions of salic and femic minerals.

Order 4 is represented by only four norms, all in order 1; in this again there is some correspondence in United States Geological Survey Professional Paper 99 though not very marked. Where femic constituents are dominant pyroxene is uniformly dominant over the iron oxides.

There are eight representatives of class V, all, as is to be expected, in orders 1 and 2.

It may be noted that of the accessory constituents magnetite and ilmenite are almost invariably present, that chromite, with one exception (III.5.5.0.), is present only in classes IV and V. Zircon, in sufficient amount for determination, is found only in two rocks, a gabbro and a pyroxenite. Apatite, never present in the silicic effusives, is also absent from the very silicic pegmatite and from some of the more silicic quartz-monzonites and granodiorites. It is almost invariably and abundantly present in the gabbro and again is missing in the pyroxenite (with one exception) and peridotite.

General statement

(1) Every class of the quantitative system is represented.
(2) There is a continuous sequence or progression of one type into another.
(3) There is a striking uniformity throughout the series in the rangs and subrangs, that is, in the relation of alkalies to lime and of soda to potash.
(4) There is a marked grouping of families.
(5) No alkalic variants are found; neither feldspathoid minerals nor soda-bearing pyroxenes or amphiboles are present in any type. The normal type is almost without exception alkali-calcic or docalcic (or percalcic) and persodic.
(6) In areal distribution the silicic types are most abundant; the subsilicic or gabbroic types are about half as abundant; the ultra-silicic and the ultra-subsilicic are the least widely distributed.

The uniformity of rang and subrang and freedom from alkalic variants seem to denote consanguinity; the chemical continuity and progression through classes and orders, and the family-grouping, or mineral association, seem to point to magmatic differentiation by crystal fractionation.

Character of the parent magma--Whether fractionation or assimilation was the dominant process operative in this differentiation, the existence of a parent magma seems an essential factor.

In these rocks the norm closely resembles the mode, differing only in the rare substitution in the norm of diopside and corundum for the modal augite.

The salic and accessory constituents are similar. The norm is therefore as useful as the mode in all discussions of generic relations and will be used in the following discussion.

Mode	Norm	Mode	Norm
Quartz	Quartz	Zircon	Zircon
Orthoclase (microcline)	Orthoclase	Apatite	Apatite
Plagioclase	Albite	Magnetite	Magnetite
	Anorthite	Ilmenite	Ilmenite
Hypersthene	Hypersthene	Chromite	Chromite
Diopside	Diopside	Hematite	Hematite
Augite	Corundum	Pyrite	Pyrite
Olivine	Olivine		

Three methods have been utilized in the determination of the probable character of the parent magma. These are:

(1) Average analyses--The derivation of an analysis from the averaging of eleven igneous types (and their subordinate varieties) which have been described, and the calculation of its norm.

A final average of six plutonic types (represented by 38 superior analyses) with the two volcanic types (eight analyses) yields the following composition and norm (see Tables 3 and 4) for II.4.3.4. Tonalite:

SiO_2	58.46	Quartz	13.26
Al_2O_3	16.10	Orthoclase	10.56
Fe_2O_3	3.21	Albite	27.77
FeO	3.27	Anorthite	23.91
MgO	4.41	Diopside	4.64
CaO	6.16	Hypersthene	1.12
Na_2O	3.31	Magnetite	4.64
K_2O	1.74	Ilmenite	1.52
H_2O	2.05	Apatite	0.34
TiO_2	0.82	H_2O	2.05
P_2O_3	0.24	Miscellaneous	0.11
Cr_2O_3	0.04		
MnO	0.12		
Miscellaneous	0.07		
Totals	100.00		99.92

This signifies a magma of dominant salic character with feldspar dominant over quartz; the alkalies and the feldspathic lime being about equal and of the alkalies soda dominant, that is, in general with the composition of a quartz-diorite, closely related also to the quartz-gabbro. It is noteworthy that its relationship to the mean of the volcanics is very close, varying only in a slightly higher percentage of salic to femic minerals in the former than in the latter magma.

(2) Review of classes, orders, rangs, and subrangs--A review of classes, orders, rangs, and subrangs represented by the norms of all types shows 16 magmatic families more silicic and 16 more subsilicic than the quartz-diorite (tonalite). The quartz-diorite occupies therefore a midway position between the more silicic and the less silicic types making up the igneous complex.

(3) Variation-diagrams--Variation-diagrams present graphically the chemical composition of the plutonic and volcanic types, separately and combined, which make up the complex of pre-Cambrian igneous rocks of eastern Pennsylvania and Maryland.

Without smoothing the lines the changing composition of the parent liquid during gravitative crystallization is plainly indicated, and scarcely needs further discussion. Crystal accumulation is apparent in the peridotite and pyroxenite lines. Conformation may be found for the subsilicic composition of the parent magma.

In Figure 5, a diagram of the norms, the rapid decline of orthoclase from the quartz-monzonite to the gabbro is a striking feature; albite is present in every plutonic type; as is also, of course, anorthite reaching its peak in the pyroxenite, while albite dominates in the quartz-diorite.

Hypersthene is present in all types reaching a remarkable peak, due to crystal accumulation, in the pyroxenite. Olivine, which has its peak in the peridotite, is the only discontinuous reaction.

Magnetite, ilmenite, and apatite are rather uniformly present until the ultra-subsilicic types are reached, when magnetite rises abruptly and definitely another indication of crystal accumulation by gravity.

(4) Crystallization of parent magma with differentiation--That there may be a continuous change in the composition of a magma subjected to change of temperature, with or without movement of the magma, has been proven by experimentation in the Geophysical Laboratory of the Carnegie Institution of Washington and described by Bowen [1]. This change is owing to fractional crystallization or fractionation, that is, the crystallization of minerals from the cooling magma in the inverse order of their relative solubilities in a changing magma. This will be, in general, in the order of basicity; under gravitative control these crystals, iron oxide, olivine, FeO-MgO and FeO-MgO-CaO pyroxene will accumulate in the lower part of the magma. Of the feldspars, lime-soda feldspar would separate first and relative movement of crystals and liquid through deformation would be operative in the development of an anorthosite body.

Crystallization in the inverse order of solubility in the continuously impoverished magma, with reactions between crystals and liquids, would give rise to the various gabbro-types, the granodiorite and the quartz-monzonite, and a residual highly silicic magma resulting from the continuous reaction of feldspar-crystals and an accompanying concentration of the so-called hyperfusibles or volatiles (H_2O, H_2S, H Cl, F, CO_2, etc.).

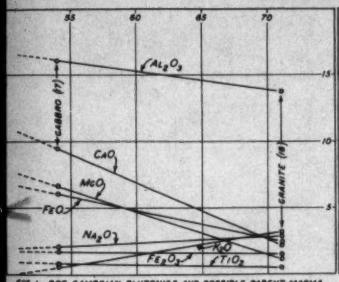

FIG. 1—PRE-CAMBRIAN PLUTONICS AND POSSIBLE PARENT-MAGMA

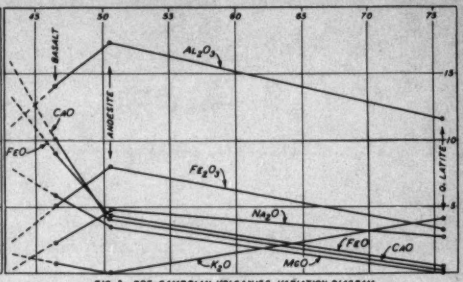

FIG. 3—PRE-CAMBRIAN VOLCANICS, VARIATION DIAGRAM

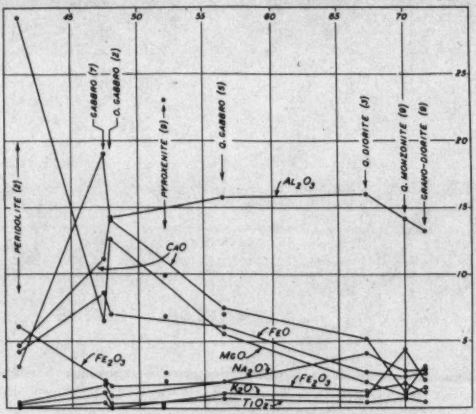

FIG. 2—PRE-CAMBRIAN PLUTONICS AND GRAVITATIVE DIFFERENTIATES, VARIATION DIAGRAM

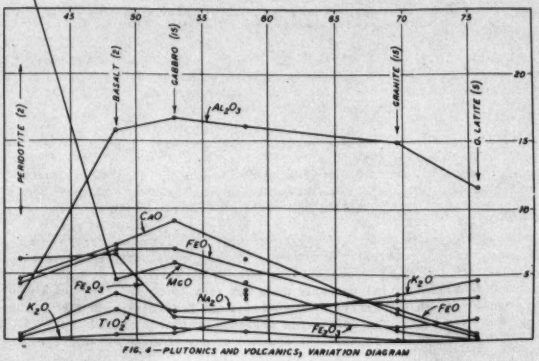

FIG. 4—PLUTONICS AND VOLCANICS, VARIATION DIAGRAM

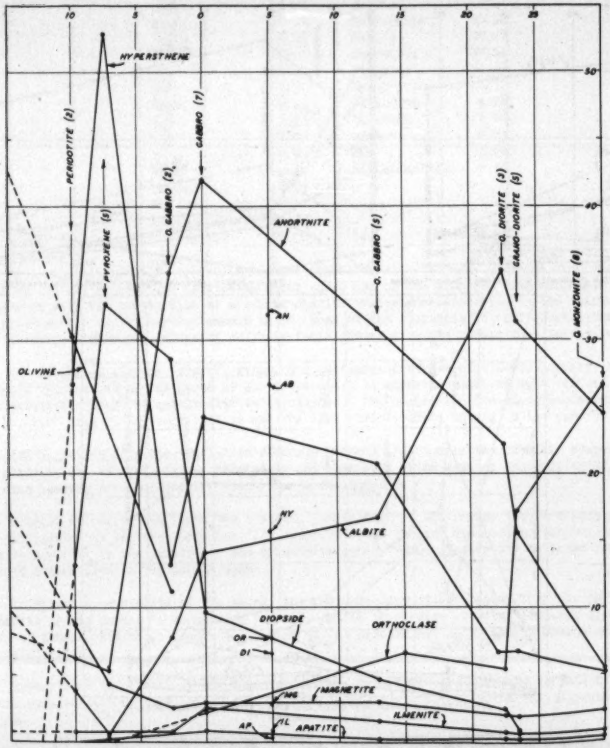

FIG. 5—VARIATION DIAGRAM OF NORMS OF PLUTONICS, MARYLAND—PENNSYLVANIA

Fractional crystallization with gravitative control is essential to the separation of quartz-bearing gabbro, granodiorite, and quartz-monzonite types. As Bowen aptly says [1] "the material required to be subtracted corresponds quite satisfactorily with the kind of crystalline material that may reasonably be supposed to have been subtracted."

The final residual liquor with a higher salic and a lower femic content than the quartz-monzonite, because of high solubility and high silicity, might remain a liquid magma until orographic movement brought about an invasion of the liquid into previously consolidated plutonics and crystalline sediments. This invasion might well be of a recurrent character with successive liquids becoming increasingly sodic-silicic and supplied with mineralizers.

In this possible history of magmatic reactions there is no demand for the enrichment of the magma in salic content at any point of crystal reaction and gravitative adjustment.

Assimilation of foreign material not only does not seem to be required but would introduce an element of discontinuity in the series of rock-types and possibly produce one or more hybrid barren types. As has been noted, the continuous sequence or procession of types is a marked feature of the igneous complex, as is also the absence of any abnormal textures such as the myrmekitic.

Resumé, order of fractionation
(1) Olivine (with gravitative separation from the magma)
(2) Pyroxene (orthorhombic) Peridotite
(3) Pyroxene (monoclinic) Pyroxenite, Olivine-gabbro
(4) Calcic plagioclase Gabbro
(5) Biotite Diorite
(6) Sodic-calcic plagioclase (anorthosite, concentration by currents)
(7) Potash feldspar and quartz Granodiorite and quartz-monzonite

Table 5--Diagrammatic presentation, mineral- and rock-sequence

Rock-type	Iron oxide	Ol.	Pyr.	Ca-Na pl.	Biot.	Na-Ca pl.	Ortho.		Quartz
Peridotite	+	+	+	> +	-	-	-		-
Olivine-gabbro	+	+	+	< +	-	-	-		-
Pyroxenite	+	-	+	> +	-	-	-		-
Quartz-gabbro									
Quartz-diorite	+	-	-	+ >	+	> +	> +	⌘	+
Granodiorite	+	-	-	-	+	+	> +	⌘	+
Quartz-monzonite	-	-	-	-	+	+	< +	⌘	+
Basalt	+	-	+	-	+	> +	-		-
Aporhyolite	+	-	-	-	+	+ <	+		+
Aplite	-	-	-	-	+	- <	+		+

The iron oxides (magnetite and ilmenite) are found in all the rock-types save the hydrothermal residual; the larger crystals separating earlier would be gravitated downward, later more minute, or even finely powdered, iron-oxide crystals might be suspended with the minerals of the quartz-diorite, granodiorite, or quartz-monzonite porridge or took part in deuteric reactions in association with mineralizers or later united in forming crystals of a more considerable size.

The lavas are presumably shorter-lived magmas than the deeper-seated plutonics; gravitative action is less complete and a concentration of volcanic gases produced the separation of the silicic lava only.

By contrast the batholith with a more prolonged life shows advanced differentiation in the multiplicity of types produced.

The anorthosite does not show intrusive relations with other formations; the mass of labradorite crystals, enmeshed in a meager viscous magma and acted upon by frictional force rather than by gravity, was moved relatively little and consolidated as a boss without intrusive contacts. The anorthosite has no dike or effusive equivalents; an anorthosite liquid apparently did not exist.

The quartz-monzonite is apparently the oldest genuine intrusive, accompanied by and merging into the granodiorite. The granodiorite-quartz-monzonite magmas, presumably filling the upper portion of the magma-chamber, probably reached a near-surface position upon relief of pressure along orogenic belts on the sides of the folds.

Upon further relief of pressure accompanying the movement and solidification of the silicic material the gabbro-magmatic porridge moved upward and intruded the consolidated granodiorite and quartz-monzonite and the crystalline sediments.

The ultra-subsilicic crystalline mass at greater depths, partially refused because of relief of pressure from above and moved upward by pressure from below, is now exposed by erosion as intrusions in the silicic and subsilicic plutonics and the sedimentaries.

That this process of partial refusion and upward movement of ultra-subsilicic material not only takes place but may be carried so far as to produce a liquid lava is proven by the effusion of limburgite-lava in the San Luis Hills peaks (personal communication from C. S. Ross) near Taos, New Mexico. Finally relatively small amounts of residual liquor, thin, rich in mineralizers and hyperfusibles, recurrently penetrated cracks and crevices in the consolidated plutonics, crystallizing with varying composition as pegmatites and aplites and still later, in successive intrusions, reacting with serpentinized peridotite to produce corundum-bodies and vermiculite-albitite veins.

The writer takes pleasure in acknowledging her obligations to G. R. Mansfield and C. S. Ross who kindly read and criticized this paper.

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ON THE ORIGIN OF THE SYENITES OF COLDWELL, ONTARIO

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Introduction

The syenites of the Coldwell District are located on the northeastern shore of Lake Superior near the Village of Coldwell (formerly called Port Coldwell), a station on the Canadian Pacific Railway. This interesting complex of alkaline rocks was first described by A. P. Coleman (Ont. Bur. Mines, v. 11, pp. 208-213, 1902) in 1901 although their presence had been suspected previous to that date due to the discovery of feldspathoid-bearing rocks in the District. Coleman was the first to call attention to the similarity of these syenites to the alkaline rocks described by C. W. Brögger (Zs. Krystallogr., v. 16, 1890) in the Oslo (Christiania) District of Norway. The most complete study of the Coldwell Area was made by H. L. Kerr (Ont. Bur. Mines, v. 19, pt. 1, pp. 194-232, 1910) during 1906 and 1907. He was unable to come to any definite conclusions regarding the petrogenesis of these rocks, but demonstrated that practically every type of the Oslo District could be duplicated in the Coldwell Area. In his report, Kerr tentatively concluded (op. cit., p. 230) that "there is reason to believe that the whole syenite-mass merely represents a peripheral differentiation phase of the fundamental gneiss (granite) found to the north."

In 1925, T. L. Walker and A. L. Parsons (University of Toronto Studies, Geol. Ser., No. 24, pp. 28-32, 1927) spent some time in the Area and described certain contact-phenomena which suggested to them that reaction of the magma with older basic rocks might have aided in the formation of the nepheline-syenites.

In recent years some of the syenites have assumed considerable commercial importance due to their utilization for building stone. The writer first became interested in the study of this igneous complex while examining claims and quarries in the syenite mass for the Ontario Department of Mines in 1930 and 1931. A representative suite of rock-specimens was collected in the course of this field-work and studied in the hope of shedding more light on the origin of this extremely complex association of alkaline rocks. The present study has not led to very convincing results, but shows that the simple conception of differentiation, as expressed by Kerr, is not easily applicable to the Area and it is thought that assimilation of older basic rocks with subsequent differentiation has had considerable effect in producing the variety of alkaline types.

The writer wishes to express his thanks to A. N. Winchell and R. C. Emmons of the Department of Geology of the University of Wisconsin for much valuable help and advice during the course of this study, and to the University of Wisconsin for granting a fellowship during part of the time that the investigation was in progress. He is also indebted to A. G. Burrows, Provincial Geologist of Ontario, for permission to use material and data collected during surveys made for the Ontario Department of Mines.

Literature pertaining to the problem

So much has been written on the origin of the alkaline rocks that lack of space prevents any discussion of the literature here. W. G. Tyrrell (The principles of petrology, E. P. Dutton and Co., New York, pp. 167-170, 1926) and S. J. Shand (Limestone and alkali rocks, Geol. Mag., v. 67, pp. 415-427, 1930) give rather complete summaries of current ideas on the subject. N. L. Bowen (J. Geol., Sup. to v. 23, 1915, and "The evolution of the igneous rocks, Princeton University Press, 1928), R. A. Daly (Igneous rocks and their origin, McGraw-Hill Co., New York, 1914), A. Harker (Natural history of igneous rocks, MacMillan Co., New York, 1909), C. H. Smyth, Jr. (Chemical composition of alkaline rocks, Amer. J. Sci., v. 36, pp. 33-46, 1913), S. J. Shand (op. cit.), J. L. Gillson (On the origin of alkaline rocks, J. Geol., v. 36, pp. 471-474, 1928), W. G. Foye (Nepheline-syenites of Haliburton County, Ontario, Amer. J. Sci., pp. 413-436, 1915), H. G. Backlund (On the mode of intrusion of deep-seated alkaline bodies, Bull. Geol. Inst., Upsala, v. 24, 1932), and many others have contributed to the subject. Various theories have been proposed to explain the petrogenesis of these rocks although the two outstanding and opposing ideas are those of assimilation of basic materials by the magma, with subsequent differentiation, as championed by Daly, and of direct crystallization-differentiation within the magma, as advocated by Bowen.

General geology of the Coldwell Area

The various rock-types in the Coldwell District and their mutual relationships have been discussed by H. L. Kerr (op. cit.) in considerable detail. The area underlain by the syenites, including the islands along the coast of Lake Superior, is probably from 100 to 125 square miles in extent. The maximum east-west dimension is almost 18 miles; the northern boundary is not well defined, but is believed never to be more than 10 miles from the railway. The region is extremely rough and rocky, consisting of rounded hills some of which rise as high as 850 feet above Lake Superior. These are scantily clad with soil and drift-material and geological examination is generally easy.

It would far exceed the scope of this paper to describe in detail the mineralogical composition of these syenites at all the various localities. In some parts of the District their extreme and rapid variation in composition is a noteworthy feature of their development. Probably few other rocks show such a diversity of types within such short distances. There are, however, certain areas, irregular in outline, which contain a particular rock-type that is free from contamination by other varieties. It is true that these areas are sometimes penetrated by occasional dike-like intrusives of another variety, but these have only a local effect. In fact, quarries are being developed at certain localities in the syenites and careful surveys have shown that as much as 60 acres in one place and 150 acres in another contain rock of such uniformity that it may be used commercially as a building stone (Jas. E. Thomson, Ont. Dept. Mines, v. 40, pt. 2, pp. 36-37, 1931). In the eastern part of the batholith an area, several square miles in extent, contains a dark augite-syenite which shows only minor variations in color, texture, and mineralogical composition.

The batholith intrudes a large area of basic igneous rocks which bound it on the east and west and occur as innumerable roof pendants of varying sizes and shapes within the batholith itself. On the north, wherever observations have been made, the syenites gradually merge into a great area of biotite-granite and gneiss.

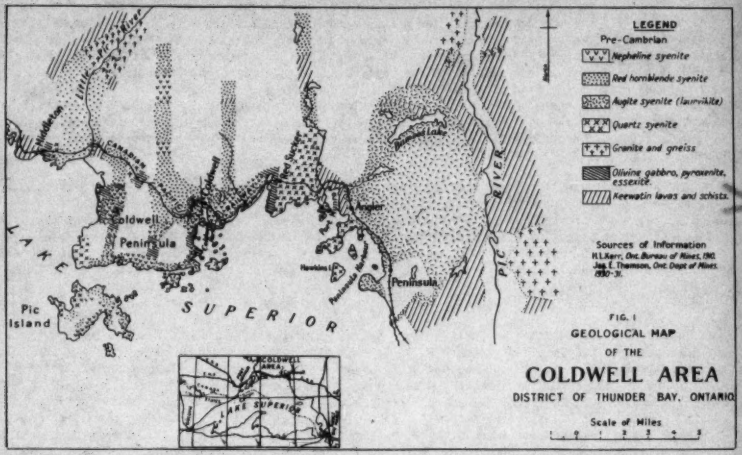

FIG. 1
GEOLOGICAL MAP
OF THE
COLDWELL AREA
DISTRICT OF THUNDER BAY, ONTARIO

The intimate association of the various syenites and granite indicates that they are all parts of one plutonic intrusion, but, for purposes of description, Kerr (op. cit.) has divided them into several fairly well-defined groups. This arbitrary grouping is used in part in the following discussion, the rocks being described so far as possible in the order of their intrusion, and correlated as closely as possible with the major divisions of the pre-Cambrian. The classification is given in Table 1.

Table 1--Formations of the Coldwell Area

Pre-Cambrian	Keweenawan	Diabase and camptonite dikes
	Intrusive contact	
	Algoman (?)	Nepheline-syenite Red hornblende-syenite Augite-syenite Quartz-syenite Biotite-granite and gneiss
	Intrusive contact	
	Pre-Algoman (?)	Olivine-gabbro, essexite, pyroxenite
	Intrusive contact (?)	
	Keewatin	Andesite, basalt, auganite, picrite, chlorite, and hornblende-schists

Keewatin lavas and schists--The Keewatin rocks are fine-grained volcanics and their metamorphosed equivalents. As previously mentioned, they border the syenites on the east and west and also occur as roof-pendants and xenoliths in the batholith. Some interesting examples of eruptive breccias are found where xenoliths of the basic materials occur in various stages of digestion by the syenites.

Olivine-gabbro, essexite, and pyroxenite--These basic plutonic rocks are largely confined to the Coldwell Peninsula, but areas are also found at Middleton and Red Sucker. Olivine-gabbro predominates, pyroxenite occurring only on the western side of the Coldwell Peninsula. Kerr (op. cit., p. 225) has described some of these rocks as essexites, although none of the sections examined by the writer contained sufficient orthoclase-feldspar to warrant the use of this name.

The typical olivine-gabbro is a medium-grained, dark-green rock which exhibits a granitic

FIG. 2—XENOLITHS OF PYROXENITE IN NEPHELINE SYENITE, WESTERN SHORE OF COLDWELL PENINSULA

texture in thin section. The mineral constituents are idiomorphic crystals of feldspar, olivine, augite, and biotite, with magnetite and apatite as accessories. Labradorite is the chief feldspar; lesser amounts of orthoclase and occasionally microcline are present. Olivine occurs in varying degrees of alteration to antigorite, but the other minerals are quite fresh in appearance. Microscopic study of the pyroxenite reveals euhedral crystals of augite, olivine, brown hornblende, and biotite with a small amount of interstitial orthoclase.

Biotite-granite and gneiss--The typical granite of the batholith is found along the Little Pic River above the first portage. In this vicinity it is a medium-grained red biotite-granite with a rather small amount of mafic constituents. The extent of the granite batholith north of the syenites is imperfectly known, as it has been crossed only along the rivers. From the fragmentary evidence obtained by early reconnaissance-surveys there appear to be at least 2000 square miles of granite and gneiss, with the possibility of several times this area (W. J. Wilson and W. H. Collins, Geol. Surv. Can., Map No. 964, 1907) although the question of whether this is all part of the batholith cannot be answered at present.

The granite consists essentially of quartz, feldspar, biotite, and hornblende with a small amount of augite and chlorite, and accessory apatite, magnetite, and zircon. The principal feldspar is orthoclase; the plagioclase is oligoclase-andesine with the composition of approximately $Ab_{70}An_{30}$. There is no evidence of microperthite, and soda-rich minerals such as are found in the syenites do not occur.

Quartz-syenite--This is a dark-red, rather fine-grained brittle rock which always contains a small amount of quartz. It closely resembles the finer-grained phases of the red hornblende-syenite and grades into it by diminution of the quartz-content. Microscopic examination of the quartz-syenite is hampered by a cloud of kaolin and red iron-oxide which invariably covers the feldspars and makes their recognition difficult. Quartz is present as anhedral grains, but is always a subordinate constituent. The feldspar is chiefly in euhedral forms of soda-orthoclase, although in some sections a delicate cryptoperthitic intergrowth of potash and soda-feldspar may be discerned. The plagioclase is andesine of the composition of approximately $Ab_{60}An_{40}$. Hornblende, augite, and biotite occur sporadically and always in small fragments. Titanite, ilmenite, and apatite are accessories.

Augite-syenite (laurvikite)--This is one of the most interesting and spectacular of the rock-types represented in the District. The color, when closely observed, is dark greenish-brown, but at a short distance is black. A striking feature is the development of tabular or lath-shaped feldspars which attain a length of one-quarter to one-half inch. The rock is at present being developed commercially as a "black granite." Much of the charm of the polished stone is due to the light-blue iridescence of the feldspars, in which respect it bears a resemblance to the beautiful monumental laurvikite of Norway.

In thin section, microperthite is found to be the chief feldspathic constituent. Soda-orthoclase and plagioclase occur sparingly, the latter being albite-oligoclase or acid oligoclase depending upon the locality. Pyroxene is represented by pale-brown augite usually bordered by deep-green, pleochroic aegirinaugite. The amphibole is generally bright-blue arfvedsonite although dark-brown barkevikite is also found. Brown biotite occurs sparingly.

Red hornblende-syenite--This name has been applied to that member of the syenite-group which is dominantly composed of crystals of red feldspar with a small amount of dark-green hornblende. The texture is variable, sometimes being medium-grained, but often of a coarse nature with lath-shaped feldspars up to one inch in length. Attempts are being made to quarry this rock for building stone and monumental purposes.

Soda-orthoclase is the chief feldspar, but a small amount of microperthite is usually found. Albite also occurs in the form of euhedral or subhedral crystals, and intergrown with the soda-orthoclase. Green hornblende is the chief ferromagnesian mineral, but small amounts of barkevikite and riebeckite are occasionally found.

Nepheline-syenite--The nepheline-syenite is a medium to coarse-grained rock varying from grey to dark grey in color and generally mottled with an orange-red decomposition-product of nepheline. Kerr (op. cit., pp. 203-204) has shown that this constituent is similar to the hydronephelite-spreustein described by Brögger (op. cit.) from the nepheline-syenites of the Oslo (Christiania) District of Norway. This mineral is abundant and very characteristic, serving as a ready means of distinguishing the presence of nepheline in a sample. Nepheline is present in amounts varying from traces to about one-sixth of the whole rock-mass. The weathered surface of the rock is characteristically pitted due to the rapidity with which nepheline decomposes.

Thin sections of the syenite reveal an association of soda-rich minerals. Microperthite, soda-orthoclase, anorthoclase, and albite are found in varying proportions. Microperthite is most abundant, whereas albite is rare. The microperthite is an intergrowth of orthoclase and albite, but only rarely may the twinning lamellae of the albite be seen. Nepheline is often almost entirely changed to its characteristic alteration-product which may be seen in all stages of development from small microscopic specks on the surface of the nepheline to irregular aggregates one-half inch in diameter. It occurs as a fine fibrous matte which makes it impossible to determine the optical properties of the mineral. Nepheline invariably occupies the irregular interstitial spaces between other constituents and was evidently the last mineral to crystallize. Pyroxene is present as subhedral crystals of augite which grade into aegirinaugite. Hornblende and occasionally bright-blue riebeckite are found, also a little biotite. Magnetite, titanite, and apatite are accessories.

Basic dikes--Most of the basic dikes of the Region are narrow, being rarely greater than seven feet and often only one foot in width. They invade all other members of the batholith. Microscopic examination shows them to be either diabase or camptonite.

Relationship of syenites and granite

Despite the gradual transition between the various syenites, occasional dikes and irregular pegmatitic offshoots of one syenite intersect another. For example, the black augite-syenite passes into red hornblende-syenite by insensible graduations. This scarcely perceptible transition is well illustrated by exposures along the railway, north of Peninsula Station. Within the transition-zone many irregular masses of pegmatitic red hornblende-syenite intrude the augite-syenite, producing a variable complex of red-brown-black syenite. Dikes of red syenite cut the augite-syenite near Middleton. It is thus evident that the red hornblende-syenite is a slightly later phase of consolidation than the augite-syenite.

Similarly, nepheline-syenite grades into red hornblende-syenite without any perceptible break. On the hill immediately north of Coldwell Station the complete transition may be seen to occur within a distance of 40 feet. The nepheline-rock is practically devoid of the feldspathoid-mineral at this point so that the only noticeable changes are those of color from grey to red and the development of the lath-shaped feldspars so typical of the red syenite. About a mile west of Coldwell along the railway a dike of nepheline-syenite six feet wide intersects the normal red hornblende-syenite. Kerr (op. cit., p. 213) has observed the same relationship near Coldwell Station and believes that the nepheline-syenite is later than both the augite- and hornblende-syenites.

It is difficult to place the quartz-syenite in the sequence. It closely resembles the finer-grained phases of the red hornblende-syenite and grades into it by diminution of the quartz-content. Kerr (op. cit., p. 230) reports that he found one dike containing quartz which intersected the nepheline-syenite. Immediately west of Coldwell Station the writer found three small quartz-containing dikes which cut the red syenite. However, there is no reason to believe that these are offshoots of the quartz-syenite. Kerr tentatively considered it as a later phase than the augite, red, and nepheline-syenite. The intimate association of the quartz- and red hornblende-syenites is such that it is sometimes quite difficult to distinguish between them. For this reason, it seems to the writer that these are really variants of one rock-type.

The granite is found in contact with red hornblende-syenite along the Little Pic River. A detailed examination was made east of the first portage to obtain the relationship of these two rocks. Traversing from the granite towards the syenite, one encounters a gradual diminution of quartz and a reciprocal increase in red orthoclase-feldspar until the red hornblende-syenite with lath-shaped crystals fully one inch in length is reached. Accompanying this transition there is a corresponding increase in the amount of hornblende from being subordinate to biotite in the granite to becoming the sole ferromagnesian constituent in the syenite. The complete change takes place within a distance of 800 feet.

While this relationship seems to be generally true in the vicinity, nevertheless, a few observations were made which show that the red hornblende-syenite is a slightly later phase of consolidation than the granite. A few narrow dikes of the syenite intersect the granite and within the syenite itself a few rounded "boulder-like" xenoliths of granite are penetrated by stringers and veinlets of the syenite. The hornblende-syenite thus bears about the same relationship to the granite as the various syenites to one another. The granite has never been found in contact with the other syenites of the batholith.

Structure of the batholith

As previously stated, the Coldwell syenites occupy only a small fraction of a great mass of granite and gneiss which has been denuded to such an extent that a few thousand square miles have been unroofed. The presence of innumerable roof-pendants and small areas of xenoliths throughout the syenites show that the present erosion-surface in this Region is very near the irregular surface of the batholithic roof, which evidently is comparatively flat yet possesses sufficient local relief to account for the heterogeneous association of intrusive and intruded rocks. The great areas of granite to the north, into which the syenites gradually merge, are doubtless deeply eroded, so that we have in this region a horizontal gradation from rocks formed at the upper surface or near the periphery of the batholith to those formed at greater depths within it. The syenites may occupy a very flat irregular bulbous stock protruding from the periphery of the main batholith, the axis of the stock dipping steeply to the north. It is also possible that the syenite-area represents only the marginal phase of a flat dome-shaped batholith which extends to the north. Whatever may be our conception of the original boundary of the intrusives, it is evident that the syenitic phase of the mass has been barely unroofed.

Origin of the syenites

Any discussion concerning the origin of the complex series of rocks in the Coldwell batholith must take into account at least three hypotheses. These include (1) the possibility that assimilation of carbonates by the granitic magma produced the desilication necessary for the formation of alkaline rocks, (2) the assimilation of the earlier basic lavas and gabbros by the intruding magma and later differentiation may have formed the syenites, or (3) they may be the result of direct differentiation from a granitic magma. These three hypotheses may be considered separately.

(1) Assimilation of carbonates--No formations containing carbonate rocks are found in the Coldwell District at present. The possibility that these covered the area at the time of the batholithic intrusion and have since been eroded away must be considered. Since the intrusion took place some time previous to the Keweenawan period there is no possibility that carbonate members of that or Palaeozoic age could have been stoped off and contaminated the magma. The Keewatin rocks which are found throughout the batholithic roof contain no carbonate members. It is possible that sedimentary rocks of the Timiskaming series may have overlain the intrusives, but wherever they are found throughout northern Ontario they are composed almost entirely of clastic material with no appreciable amount of carbonates. The Huronian formations of the north shore of Lake Huron contain carbonate members (W. H. Collins, Geol. Surv. Can., Mem. 143, 1925). Since it is probable that the batholithic invasion took place some time during the Algoman period of plutonic disturbance, it would thus be earlier than the deposition of the Huronian series. The nearest area of Huronian rocks is found along the shore of Lake Superior north of Sault Ste. Marie. These are 150 miles to the south of the Coldwell District.

Another factor must be considered. It is apparent that the Coldwell syenites are only partly unroofed since they contain many isolated roof-pendants of older basic rocks. It thus seems logical to assume that these greenstones and gabbroic rocks once covered most of the area which the syenites now occupy. If the lavas and gabbros were of any appreciable thickness, it is probable that only a very small amount of the intrusive mass ever came in contact with formations above them. As the syenites must have consolidated at depths which were truly plutonic, the overlying greenstones, gabbros, and associated rocks must have been several thousands of feet in thickness when active upward movement of the magma ceased. It thus seems highly improbable

Table 2--Analyses of the various rocks in the Coldwell District

Rock	Augite-syenite			Nepheline-syenite			Red syenite	Quartz-syenite		Granite	Olivine-gabbro
Specimen	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11
SiO_2	58.37	58.81	57.36	55.59	55.11	53.12	57.58	60.21	58.60	65.84	42.83
Al_2O_3	15.11	13.37	15.18	23.55	16.76	18.40	14.91	15.65	19.94	17.16	17.19
Fe_2O_3	1.91	3.88	1.51	.....	2.18	7.46	2.47	5.70	4.25	1.44	5.91
FeO	8.99	6.97	8.88	3.28	5.72	5.10	7.79	3.15	2.42	2.11	7.76
CaO	3.32	3.89	4.16	1.87	6.65	2.93	3.21	2.74	2.76	2.70	11.16
MgO	0.57	0.51	0.40	0.78	3.20	0.80	1.14	1.57	1.71	1.49	3.99
Na_2O	3.76	4.96	4.59	8.05	3.98	6.49	4.45	4.33	3.24	3.94	2.96
K_2O	4.09	5.42	4.90	5.04	3.25	2.87	4.75	4.34	4.84	3.68	0.77
P_2O_5	0.21	0.31	0.15	.....	0.49	trace	0.16	0.12	.....	0.09	1.95
TiO_2	0.97	0.70	0.96	.....	0.78	0.40	0.81	1.05	.....	0.63	2.67
CO_2	.....	.....	0.49	.....	.....	0.25	0.66	nil	.....	nil	0.39
H_2O	2.25	1.04	0.99	1.21	1.66	1.61	1.65	1.12	2.29	0.96	1.74
FeS_2	.....	.....	0.26	.....	.....	.....	0.28	.....	.....	.....	.....
MnO	0.48	0.20	0.21	0.45	0.28	0.12	0.23	.....	.....	.....	0.20
BaO	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.30
S	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.25
Total	100.03	100.06	100.04	100.15	100.07	99.55	100.09	99.98	100.05	100.04	100.07[a]

[a]Less O = 99.98.

The specimens and references of Table 2 according to number are as follows:

1--Near Peninsula; Ont. Bur. Mines, v. 19, pt. 1, p. 220, 1910; F. A. Ghent, analyst.
2--Near Peninsula; Ont. Bur. Mines, v. 11, p. 211, 1902; A. H. A. Robinson, analyst.
3--Black Granite Quarry, Peninsula Harbor; Ont. Dept. Mines, v. 40, pt. 2, p. 37, 1931; T. E. Rothwell, analyst.
4--East of Coldwell Station; Ont. Bur. Mines, v. 19, pt. 1, p. 209, 1910; E. L. C. Forster, analyst.
5--West of Coldwell Station; Ont. Bur. Mines, v. 19, pt. 1, p. 209, 1910; F. A. Genth, analyst.
6--East shore of Coldwell Peninsula; University of Toronto Studies, Geol. Ser., No. 24, p. 30; H. C. Rickaby, analyst.
7--Red Granite Quarry, Peninsula; Ont. Dept. Mines, v. 40, pt. 2, p. 38, 1931; T. E. Rothwell, analyst.
8--Hawkins Island, Lake Superior; W. K. McNeill, analyst.
9--Red Sucker; Ont. Bur. Mines, v. 19, pt. 1, p. 222, 1910.
10--Between first and second portages, Little Pic River; W. K. McNeill, analyst.
11--East of Middleton Station, Rockefeller Laboratory for Rock-Analyses, Minneapolis, Minn.; T. Kameda, analyst.

that any amounts of carbonate rocks could have been assimilated from above even if they actually had overlain the syenites at the time of their formation.

These field-relationships indicate that assimilation of carbonates on a scale sufficient to desilicate an area 100 to 125 square miles in surface extent in the Coldwell District is well-nigh impossible.

(2) Assimilation of basic igneous rocks--R. A. Daly (Igneous rocks and their origin, p. 404, 1914) has pointed out that basic igneous formations may exert desilicating effects on batholithic magmas sufficient to form syenites. In fact, in his statistical studies of the field-associations of these types he points to the Keewatin country rock associated with the Coldwell syenites as probably being a significant factor in their genesis (ibid., p. 487).

Field-evidence of assimilation--Everywhere throughout the batholith evidence of digestion of gabbroic rocks or basic lavas may be seen. A description of the assimilation-phenomena at a few localities is given below, but it could be duplicated manyfold for various parts of the District.

On the shore of Lake Superior, south of the mouth of the Little Pic River, a considerable area of rock has been washed bare by the waves, revealing the relationships perfectly. The basic rock at this location is a peculiar variety of pyroxenite containing a certain amount of orthoclase. It is intruded by a light-colored, coarse-textured nepheline-syenite which contains an abundance of brick-red hydronephelite-spreustein. Distinct pegmatitic dikes may be traced from

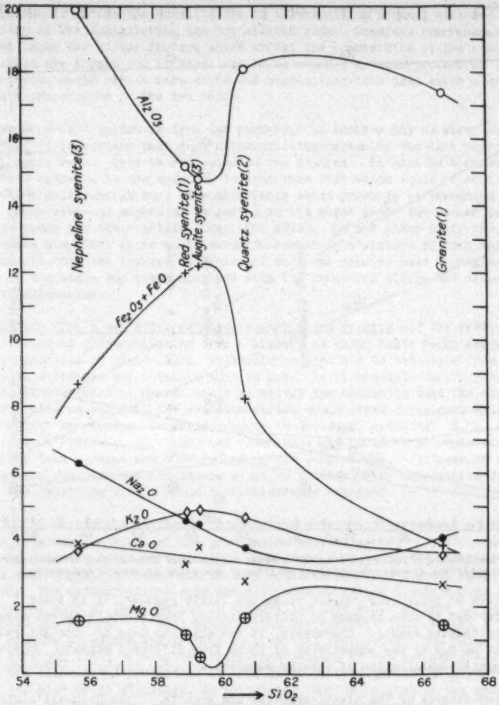

FIG. 3—VARIATION-DIAGRAM OF COLDWELL SYENITES AND GRANITE (NUMBERS IN PARENTHESES INDICATE NUMBER OF ANALYSES AVERAGED)

the body of syenite into the basic rock. Small xenoliths are abundant in the nepheline-syenite near the contact. They are always rounded and exhibit a sharp contact with the syenite. They range in diameter from a few inches to a couple of feet and are separated by areas of nepheline-syenite which sometimes show flow-structure as if a viscous mass of magma had been squeezed between the blocks. The syenite in the contact-zone is darker in color and contains a greater percentage of hornblende and nepheline than usual. The olivine and augite of the basic rock have disappeared entirely and hornblende is practically the sole ferromagnesian mineral.

Essentially the same assimilation-phenomena were noticed at Red Sucker and in Coldwell Harbor. At Red Sucker, olivine-gabbro feathers out and gradually disappears into the syenite. Again, green hornblende is developed in large amounts, becoming less conspicuous at a short distance from the contact and finally it is not noticed in excess of the ordinary amount of hornblende in the normal nepheline-syenite. Thin sections of the syenite at the contact show numerous clusters of small subhedral hornblende-crystals, but the olivine and most of the augite of the gabbro have disappeared. Also the labradorite-feldspar of the gabbro is replaced by the microperthite and soda-orthoclase of the syenite.

Study of variation-diagrams--The nature of the magma and the chemical relationship of the various rock-types derived from it may be best apprehended by use of a variation-diagram. Petrologists have found these to be particularly serviceable in distinguishing changes brought about by differentiation as distinct from those caused by addition of foreign matter. When the

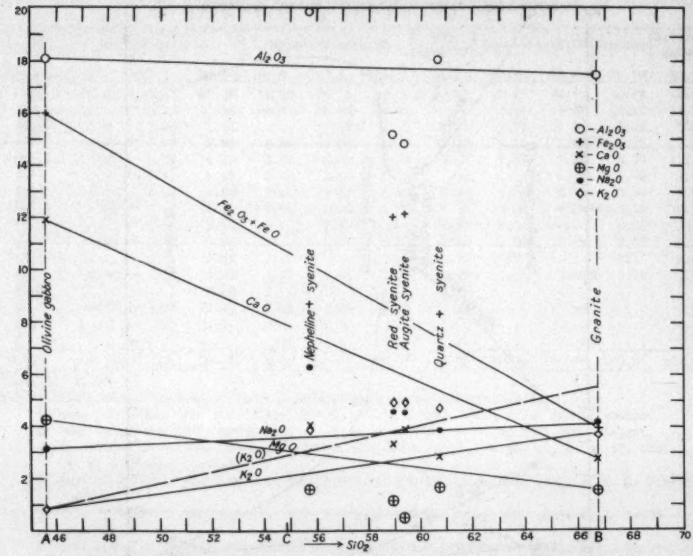

FIG. 4—VARIATION-DIAGRAM OF COLDWELL SYENITES SHOWING THEIR ACTUAL COMPOSITIONS AS COMPARED WITH THEIR THEORETICAL COMPOSITION IF FORMED BY STRAIGHT ADMIXTURE OF GRANITE AND GABBRO

curves for a series of supposedly related rocks are fairly regular, it is thought that the assemblage has been derived by some process of differentiation from a common parent magma, or from a number of closely related magmas. Conversely, if the analyses have no constant relations, their irregularity must be due to the association of rocks from different magmatic sources or has been produced by extensive assimilation of foreign material.

The variation-diagram of the alkali-syenites and granite of the Coldwell District is shown in Figure 3. The analyses were taken from Table 2 and averaged for each rock-type. The total of the two iron oxides is expressed as ferric oxide and to this manganese oxide has been added. The analyses were then recalculated to 100, water and carbon dioxide being omitted.

It will be noticed that the curves are generally quite irregular. When compared with curves in the diagrams shown by A. Harker (Natural history of igneous rocks, pp. 118-140, 1909) and others for certain cases of differentiation, these exhibit an irregularity that suggests the influence of some factor other than straight crystallization-differentiation. Since the field-relationships indicate that the various phases of the batholith are obviously closely related genetically there is little possibility here that we are dealing with separate intrusives. The only other possible inference is that foreign material has contaminated the magma. If such a surmise is correct, then what was the nature of the initial common magma? Since the syenites occupy only a small fraction of a great granite batholith, probably constituting about one per cent of the whole, it is logical to assume that the normal parent magma was granitic in composition.

In Figure 4, an attempt is made to study the effects of the admixture of granite and one of the basic rocks, olivine-gabbro. The variation-diagram shows by straight lines the theoretical amount of each oxide-constituent that should result from mixing any proportion of granite and gabbro. The percentages of these constituents in the syenites, as recalculated from chemical analyses, are also plotted. It will be seen that none of the constituents is present in the theoretical proportion demanded for straight admixture. This is in accordance with what might be expected. It has been clearly demonstrated by A. Harker (op. cit., pp. 335-359) that when two

rock-types are mixed in nature the constituents of the resulting product will not be present as a fixed proportion of the assimilating and assimilated rock. Chemical rearrangement and probably diffusion are at least two of the factors which affect the composition of the resulting hybrid rock. New minerals are formed and if these should be removed by some process of differentiation, the residual material would have a very different composition from that which might be calculated by mixing certain proportions of the two rocks.

Inasmuch as a perfect gradation from one rock-type to another may be observed everywhere in the Coldwell Area, it is certain that some differentiation actually did take place after incorporation of any basic rock. This is reflected in the diagram. It will be noticed that the amount of lime and magnesia in the syenites is less than that which would be ordinarily expected from a mixture of granite and gabbro. The deficiency would probably be accounted for by the sinking of the heavy lime and magnesian silicates in the magma after the manner postulated by R. A. Daly (Igneous rocks and their origin, Chap. 20, 1914). On the other hand, there is an excess of soda and potassa over that which would normally result from mixture of such materials. Here again it is possible that the lighter molecules of soda and potassa have segregated towards the uppermost part of the magma and there combined with the remaining silica and alumina to form feldspars and feldspathoids.

Differentiation from a syntectic of olivine-gabbro and granite--If the syenite complex were produced by some sort of differentiation from a mixture of older basic rocks assimilated in a magma originally granitic in composition, it should be possible to calculate from the available information how this process was actually carried out. Is it possible that crystallization-differentiation, as advocated by Bowen, could so affect the syntectic that the sinking of mineral constituents precipitated early in the reaction-series would leave a residual magma of such an alkaline nature that, on cooling, it would produce the Coldwell syenites? N. L. Bowen (The evolution of the igneous rocks, p. 60, 1928) has shown that the earliest minerals of the reaction-series to separate from a magma are olivine and calcic plagioclase. If these or other early-formed minerals were removed from the liquid magma by gravity or by deformative forces, the composition of the remaining liquid would be considerably changed.

In Table 3, the writer has attempted to study the effect of the removal of these early-formed minerals from any syntectic of the granite and olivine-gabbro of the Coldwell District. The object was to find out if it were possible to produce rocks with the chemical composition of the syenites by such a process. Inasmuch as this would necessitate a great number of "cut-and-try" calculations, the determinations were actually made by adding minerals such as olivine and basic plagioclase to each of the syenites in proportions that would attempt to approximate some mixture of granite and gabbro. It will be seen that any vertical line between A and B in Figure 4 represents a mixture of gabbro and granite in a certain proportion. The point of intersection of the various straight lines joining the oxide-constituents of the end-members with this vertical line will give the theoretical percentage of each oxide in this particular mixture. Thus, any mixture of syenite plus basic silicates, as calculated, may be checked on the graph against the theoretical mixture of gabbro and granite which has the same SiO_2 content.

For purposes of illustration the case of the red hornblende-syenite (Table 3) may be considered. The recalculated chemical analysis of the rock as expressed in the variation-diagram (Fig. 3) was used as it takes into account only the more important oxide constituents. To these oxides were added forsterite in the proportions of $MgO:SiO_2 = 1:0.75$ by weight, as demanded by the chemical formula Mg_2SiO_4. In the same way fayalite, plagioclase, and wollastonite were added, each in the proper proportion of oxide-constituents by weight as calculated from the chemical formula. The total mixture was then reduced to 100 per cent and compared with the mixture of granite and gabbro which has the corresponding SiO_2 content in Figure 4. The difference between the "cut-and-try" calculation and the theoretical mixture is recorded in the last column.

Many successive approximations were made for each syenite by adding those basic silicates which are thought to separate early from a magma. These were added in varying proportions, amounts, and combinations. The results given in Table 3 represent only those approximations which gave the best agreement between the calculated and theoretical mixtures. By continuing these successive approximations an even closer correspondence between the calculated and theoretical mixtures could probably be obtained.

The results indicate that it is possible to add certain minerals to the syenites and produce a rock which approximates very closely the composition of a syntectic of granite and gabbro. The writer does not wish to imply that the combination of minerals added to the syenites in the accompanying tables are the only ones which would approximate the corresponding syntectic. It is possible that if sufficient time and care were taken other combinations of basic silicates could be found which would give similar results.

Table 3--Showing how the syenites of Coldwell may be derived by the removal of basic silicates from a syntectic of granite and gabbro

Material	Recalculated analysis	Materials added to the syenite					Total	Reduced to 100 o/o	Corr. mix. of granite and gabbro	Difference
		Forsterite	Fayalite	Albite	Anorthite	Wollastonite				
	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o	o/o
					Red hornblende-syenite					
SiO_2	58.9	2.1	1.3	2.9	10.7	2.7	78.6	54.8	54.8	0.0
Al_2O_3	15.2	...	...	0.8	9.1	...	25.1	17.5	17.8	-0.3
Fe_2O_3	12.0	...	3.3[a]	...	....	...	15.3	10.6	10.7	-0.1
CaO	3.3	...	...	...	5.0	2.5	10.8	7.6	7.9	-0.3
MgO	1.2	2.8	...	...	....	...	4.0	2.8	3.1	-0.3
Na_2O	4.6	...	...	0.5	....	...	5.1	3.5	3.5	0.0
K_2O	4.8	...	...	...	....	...	4.8	3.3	2.1	+1.2
Total	100.0	...	...	...	....	...	143.7	100.1	99.9	...
					Augite-syenite					
SiO_2	59.3	2.4	...	2.9	8.5	2.1	75.2	56.3	56.3	0.0
Al_2O_3	14.8	...	...	0.8	7.3	...	22.9	17.2	17.8	-0.6
Fe_2O_3	12.2	...	...	...	....	...	12.2	9.1	9.8	-0.7
CaO	3.8	...	...	...	4.0	2.0	9.8	7.3	7.2	+0.1
MgO	0.5	3.2	...	...	....	...	3.7	2.8	2.9	-0.1
Na_2O	4.5	...	...	0.5	....	...	5.0	3.7	3.6	+0.1
K_2O	4.9	...	...	...	....	...	4.9	3.6	2.3	+1.3
Total	100.0	...	...	...	....	...	133.7	100.0	99.9	...
					Quartz-syenite					
SiO_2	60.7	1.8	2.0	5.8	....	3.7	81.5	56.4	56.4	0.0
Al_2O_3	18.1	...	...	1.7	....	...	26.2	18.0	17.8	+0.2
Fe_2O_3	8.2	...	5.4[b]	...	....	...	13.6	9.4	9.8	-0.4
CaO	2.8	...	...	...	....	3.5	9.8	6.8	7.2	-0.4
MgO	1.7	2.4	...	...	....	...	4.1	2.8	2.8	0.0
Na_2O	3.8	...	...	1.0	....	...	4.8	3.3	3.6	-0.3
K_2O	4.7	...	...	...	....	...	4.7	3.2	2.3	+0.9
Total	100.0	...	...	...	....	...	144.7	99.9	100.2	...
					Nepheline-syenite					
SiO_2	55.7	2.8	4.9	...	10.7	6.4	80.5	49.9	49.9	0.0
Al_2O_3	19.9	...	...	...	9.1	...	29.0	18.0	18.0	0.0
Fe_2O_3	8.7	...	13.0[c]	...	....	...	21.7	13.4	13.5	-0.1
CaO	3.9	...	...	...	5.0	6.0	14.9	9.3	10.0	-0.7
MgO	1.6	3.7	...	...	....	...	5.3	3.3	3.7	-0.4
Na_2O	6.3	...	...	...	....	...	6.3	3.9	3.5	+0.4
K_2O	3.8	...	...	...	....	...	3.8	2.3	1.4	+0.9
Total	99.9	...	...	...	....	...	161.5	100.1	100.0	...

[a]FeO, 3.0 per cent. [b]FeO, 4.8 per cent. [c]FeO, 11.7 per cent.

Notes: Forsterite. Mg_2SiO_4. $MgO:SiO_2$ = 1:0.75 (by weight).
Fayalite. Fe_2SiO_4. $FeO:SiO_2$ = 1:0.42 (by weight).
Albite. $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$ $Na_2O:Al_2O_3:SiO_2$ = 1:1.65:5.81 (by weight).
Anorthite. $CaO \cdot Al_2O_3 \cdot 2SiO_2$. $CaO:Al_2O_3:SiO_2$ = 1:1.82:2.14 (by weight).
Wollastonite. $CaO \cdot SiO_2$. $CaO:SiO_2$ = 1:1.07 (by weight).

It will be noticed that in every case the discrepancy between the K_2O in the calculated and theoretical mixtures is much greater than that of the other constituents. This proved to be very puzzling and eventually led to the suspicion that probably the content of K_2O as recorded in either the olivine-gabbro or granite was not representative of the rock-type. As the writer had Rosiwal's analyses of these rocks available, it was possible to make a rough check on this constituent. Two Rosiwal analyses of the granite from locations a short distance apart, but from the same general vicinity as the sample taken for chemical analysis, showed a content of 52.4 and 54.0 per cent orthoclase, respectively; this is theoretically equivalent to 8.9 per cent K_2O in the granite. As Na_2O may replace K_2O up to about 30 per cent in orthoclase and K_2O may replace Na_2O to a small extent in plagioclase, the actual amount of K_2O present is difficult to estimate. Even if it is assumed that K_2O is replaced to the extent of 30 per cent or even more by Na_2O in the orthoclase, there would still be 5 and 6 per cent K_2O in the granite. If we take a very minimum of 5.5 per cent and substitute this value for the K_2O in Figure 4, the broken line repre-

sents all variations of K_2O between granite and gabbro. Using this approximation as the theoretical amount of K_2O in all mixtures, it was found to check in the various tables within the same limits as the other constituents.

Interpretation of results--The significance of the calculations in these tables is seen by reasoning back from the result. The case of the red hornblende-syenite (Table 3) may be considered for illustrative purposes. The Table shows that if wollastonite, anorthite ($Ab_{10}An_{90}$), fayalite, and forsterite are removed from a syntectic of granite and gabbro which contains 54.8 per cent SiO_2 the residual liquid would have the approximate composition of red syenite. As previously mentioned, Bowen has pointed out that olivine and basic plagioclase are amongst the first minerals to separate from a cooling magma in which fractional differentiation is taking place. It is quite possible that a lime-silicate such as wollastonite could also be removed. In some of the calculations the writer added diopside to the above group and secured a fairly close correspondence between calculated and theoretical values, but the disagreement was greater than in the cases recorded.

The results should be regarded as a possible explanation of the derivation of the various syenites in the Coldwell Area. They show that it is perfectly possible for fractional crystallization to produce each of the syenites by removal of early-formed crystals from a syntectic of granite and gabbro. The type of syenite produced at one particular place, according to this interpretation, would be a direct function of the amount of assimilation at that point together with the amount of fractional crystallization that followed. This could be expected to produce a great variety of rock-types with complex relationships. The writer has stated in an earlier part of this paper that within the Coldwell batholith the extreme and rapid variation of syenitic types is one of the most noteworthy features in their development.

The amount of assimilation necessary to produce the syntectic from which any syenite is formed by later differentiation may be calculated approximately from the graph (Fig. 4). Consider again the case of red hornblende-syenite. To produce red syenite with the SiO_2 content indicated at the point C (54.8 per cent), it is necessary to mix granite and gabbro in the proportions of granite: gabbro = AC : BC, that is, 9.2 parts of granite by weight must assimilate 11.9 parts gabbro by weight. Assuming the relative densities of granite and gabbro to be 2.65 and 2.94, respectively, it is calculated that 1.0 part of granite by volume must assimilate 1.2 parts gabbro by volume to obtain the silica-content of the red hornblende-syenite. Similarly, it may be calculated that 1.0 part of granite by volume must dissolve 0.9, 0.9, and 3.5 parts by volume of gabbro to obtain the silica-content of the quartz-syenite, augite-syenite, and nepheline-syenite, respectively.

All the above calculations have been based on the effects of assimilation of only one of the older basic rocks in the Coldwell District. While the olivine-gabbro occurs widely in certain parts of the Area and especially in the vicinity of nepheline-syenite, it has been shown earlier in this paper that such other basic types as picrite, basalt, andesite, auganite, and chlorite- and hornblende-schists are common. No attempt has been made to study in detail the effect of each of these types on the magma. Since their chemical composition is similar, in general, to that of the olivine-gabbro, it is assumed that the effects of assimilation of these rocks would not be very different from those already discussed.

The question of superheat--Some petrologists have raised a blanket objection to the effects of large-scale assimilation on account of the general lack of magmatic superheat necessary for the digestion of large amounts of foreign material. Regarding the amount of heat available in a magma and its effect on inclusions, N. L. Bowen says (The evolution of the igneous rocks, p. 183, 1928): "If we make a liberal assumption that it (the magma) is superheated 100° (say its temperature is 1100° and the saturation-temperature 1000°) and that this condition is acquired when it has reached a level 5 km below the surface, it should be noted that the mere immersion of blocks of country rock amounting to about 10 per cent of the mass of the magma would be sufficient to wipe out this superheat, for the original temperature of blocks even at this quite considerable depth would be only 200°."

Experimental investigation by John Stansfield (Assimilation and petrogenesis, Valley Publishing Co., Urbana, Ill., p. 137) has shown that assimilation of certain minerals by magmas is readily accomplished, but to a restricted extent. He agrees with Bowen that 10 to 15 per cent may be the limit of the amount of foreign rock matter which has been assimilated by natural magmas.

From this it would seem impossible for granite to assimilate basic rocks to the extent of 90 to 350 per cent of its volume, as demanded according to the foregoing calculations. However,

the above figures for the amount of assimilation apply only locally and take no account of the relative volumes of granite and syenite masses in the batholith. In the Coldwell batholith if only surface-area is considered, the ratio of syenites to granite is, at a maximum, about 1:20 and may even be as small as 1:100. When considered in three dimensions the volume of the syenites may even be less than 1/1000 of the granite. If it is considered that the syenites are located at the roof of a batholith which is now only partially uncapped and that they have been formed by the stoping of the overlying basic rocks, the probability is very great that they do not extend to any great depth, but grade into normal granite in the same way as they grade laterally into normal granite. When viewed from this angle, the actual amount of assimilated material compared with the total amount of magma may be well within the limits set by Bowen, even in the case of the nepheline-syenite.

S. J. Shand (Geol. Mag., v. 67, pp. 415-426, 1930) has argued that there is no theoretical objection to the proposition that a large body of granitic magma would have sufficient superheat to give rise to a much smaller body of feldspathoidal magma by reaction with basic material. He cites numerous cases where alkaline rocks are thought to have been formed by assimilation of limestone in granite-magma. In all of these instances the ratio of alkaline rocks to granite is very small.

Summary--While the above statements do not constitute proof that assimilation has played a dominant role in the petrogenesis of the Coldwell alkali-complex, yet they show that it may have been a factor which has been operative and may have had considerable effect upon the magma. It has been demonstrated that the removal of early-formed crystals such as olivine and basic plagioclase from various syntectics of granite and gabbro could produce residual liquids very similar in composition to the syenite types. Field-relationships show an extremely close association between the older basic rocks and the syenites. In detailed study of the nepheline-syenite there is an appreciable development of nepheline near xenoliths. Variation-diagrams show that some foreign material has been introduced to produce the pronounced irregularities of chemical composition in these rocks. There is no reason to believe that the magma did not possess sufficient superheat to incorporate a considerable amount of basic igneous rocks. When it is remembered that the syenites represent the upper surface of a great batholith, being probably a thin veneer over a granitic subsurface, and also that there is widespread evidence of assimilation on this upper surface, it is only natural that hybrid rocks of a great variety would result and sudden transitions from one type to another would be common. In short, there is no evidence that the alkaline magma could not have been formed by assimilation of foreign material with later differentiation while the available facts are rather suggestive that it was so produced.

(3) Differentiation--It has already been pointed out that the variation-diagram of the Coldwell plutonic rocks shows no regular linear variation of constituents to suggest that they represent a differentiation-series from a common magma. Nevertheless, they have been described as possibly representing a marginal differentiation phase of the granite (H. L. Kerr, op. cit., p. 230), so that this mode of origin must be considered.

The marked similarity of the Coldwell syenites to those described by W. C. Brögger (Zs. Krystallogr., v. 16, 1890) in the Oslo (Christiania) District of Norway is shown in Table 4.

Table 4--Similarity of Coldwell and Oslo syenites

Succession of rock-types	
Coldwell District (after Kerr)	Oslo District (after Brögger)
Basic dikes	Basic dikes
Granite	Granite
	Soda-granite
Quartz-syenite	Nordmarkite } that is, quartz-syenites
	Akerite }
Nepheline-syenite	Laurdalite (nepheline-syenite)
Red hornblende-syenite	
Augite-syenite (laurvikite)	Laurvikite
Essexite, picrite, olivine-gabbro, basalt, diorite, etc.	Gabbro, diabase, melaphyre, camptonite, spilite, etc.

Kerr's evidence for the succession of syenites at Coldwell has already been discussed. He did not note any age-relationships of the granite to the syenites, but tentatively placed it in the position corresponding to Brögger's granites. As previously mentioned, the writer's observations suggest that the granite is a slightly earlier phase than the syenites.

According to Brögger (ibid., pp. 80-90) the Norwegian alkaline rocks were formed by a series of eruptions from a common parent magma, thus producing a continuous succession from basic rocks through alkaline syenites to granites. In the light of modern ideas concerning crystallization-differentiation, this mode of origin seems almost impossible. Beginning with a normal sub-alkaline magma, as crystallization proceeds it must become sufficiently undersaturated to precipitate feldspathoids and then suddenly begin to precipitate quartzose-syenites and finally granite. Thus, from an area of syenites 100 to 125 square miles in extent in the Coldwell District an area of granite 20 to 100 times its size would have to be differentiated.

If the alternate view that the syenites were derived from a great area of granite by fractional differentiation is considered, there is no well-supported explanation of the desilication of the magma necessary to precipitate feldspathoids. Bowen's first theory (J. Geol., Sup. to v. 23, p. 55, 1915) of direct differentiation to produce feldspathoid-bearing rocks from the crystallization of large bodies of sub-alkaline magma has been attacked as being contrary to the facts as observed in nature. It has been pointed out that residues from the crystallization of such bodies are universally found to be highly siliceous. Bowen's second theory (Evolution of the igneous rocks, Chap. 12, 1928) resolves itself into a discussion on the derivation of rocks enriched in leucite, which in any case are of minor importance. It seems that no very logical explanation of this important step has been made except by Daly. S. J. Shand (Geol. Mag., v. 67, p. 428, 1930) has aptly summarized our present knowledge regarding the origin of alkaline rocks as follows: "Up to a certain point Daly's theory has been proved to be correct; beyond that point the choice lies between Daly's theory and no theory at all."

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NATIONAL RESEARCH COUNCIL

TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION
SIXTEENTH ANNUAL MEETING
APRIL 25 AND 26, 1935
WASHINGTON, D. C.

PART II
REPORTS AND PAPERS
SECTION OF HYDROLOGY

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REPORT OF THE COMMITTEE ON SNOW, 1934-35

J. E. Church, Chairman

Organization

As noted in the last annual report (1), the personnel of the Committee on Snow was chosen to represent not only districts and large watersheds but also phases of interest. These phases deal mostly with the forecasting of water-supplies in lakes and streams. Other phases include general snow-studies, ice-engineering, glaciers, and polar exploration. To these should be added snow-removal, flood-forecasting, and the conservation of snow. The last, namely, the conservation of snow, has now been placed under the supervision of Joseph Kittredge, Jr., Professor of Forestry, University of California, who has been added to the personnel of the Committee.

Progress

Progress has been marked by a strong upswing, partly emergency, partly permanent. How much there is of the former, only time can determine. The National Resources Board has laid wide foundations in the report of its Land and Water Planning Committees.

Large projects have also been inaugurated in the Tennessee, Missouri, and Columbia basins for power and control of navigation. The Colorado River Project long under consideration at Boulder Dam is now approaching completion. The Great Valley Project of California is growing insistent. The Kennett Dam on the Sacramento has become inevitable because of the needs of navigation and the Government's interest in it. Upstream storage in the Tahoe-Truckee Basin, California and Nevada, is becoming an assured fact after a quarter-century of slow adjustment. In the case of all these, except the Tennessee Basin, snow-surveying is essential to their efficient regulation. Indeed, in the Tahoe-Truckee Basin final agreement between discordant interests as to the control of the level of Lake Tahoe and the efficient use of the water was made possible only by the long-continued accuracy of the forecasts based on snow-surveying.

The states also that withdrew from cooperation owing to the desperate lack of funds during the previous biennium are now resuming the work. Nevada has already made an appropriation for both cooperative snow-surveying and stream-gaging. The California State Legislature has made an appropriation of $15,000 for the next biennium to resume snow-surveying; this will be available as soon as agencies usually cooperating with the Division of Water Resources agree to continue their cooperation. In Utah the cooperative group, consisting of the Agricultural Experiment Station, the United States Forest Service, and the United States Weather Bureau, has now been joined by the State Engineer and has finally received a State appropriation. Oregon has resumed cooperative snow-surveys with the counties.

Progress in the Upper Missouri and Columbia basins has been steady. In the Missouri, the United States Army Engineer Corps at Kansas City is receiving cooperative aid from the United States Geological Survey, the Montana Agricultural Experiment Station, and power-companies. In the Columbia, the United States Army Engineer Corps at Portland is earnestly discussing the establishing of a complete snow-survey system to aid in regulating Bonneville Dam near the Dalles, and is already receiving cooperation from the State of Oregon and also from British Columbia, which has now established snow-survey courses on the headwaters of this stream. The presence of Grand Coulee Dam will expedite the surveys. In the Colorado Basin a plan of snow-surveying has now been formulated by the United States Bureau of Reclamation, which will inaugurate the system unless the United States Weather Bureau or other organizations undertake the task.

Recently the Division of Irrigation of the Bureau of Agricultural Engineering of the United States Department of Agriculture has entered snow-surveying and promises to be one of the most active cooperators in the work. Under W. W. McLaughlin and James C. Marr the Bureau is drawing together the various phases of snow-surveying of the western states and plans a cooperative set-up of national character. As one of the first steps in the new plan the Chairman of the Committee on Snow has toured the West in company with Carl Elges, Jr., of the Nevada Agricultural Experiment Station, to investigate snow-survey problems. The problem of the Colorado River has been examined in detail. This trip, sponsored by the Bureau of Agricultural Engineering and the Nevada Agricultural Experiment Station, promises to be particularly fruitful.

Regional reports

Greater details are given in the following regional reports by members of the Committee or others in close touch with conditions.

New England (Paul L. Bean)

Accumulation of snowfall in northern Maine and New Hampshire commenced about December 10, 1934, and shows for the winter of 1934 and 1935 about average conditions. The snow cover was slow in building up to an average amount until the winter was well advanced.

The drainage-areas in this section of the country are utilized to collect water in the storage-reservoirs which supply the water used in regulating the rivers flowing from this area to the sea. Inasmuch as this snow reserve is the main source of supply for regulating the flow during the summer months, the slow accumulation during the past winter was a matter of grave concern, especially in view of the dry conditions prevailing in the country to the west of this area. However, our snow-surveys were the means of knowing the exact conditions prevailing and enabled us to draw on our reserves with intelligent foresight. I believe that without these surveys serious shortages in water-supply would occur periodically in this area.

The snow cover increased to an average amount up to February 15, 1935. Since this date, there has been a marked deficiency in precipitation. This deficiency has now continued for six weeks and is very severe in intensity.

Snow-surveys have been carried on over an area of at least 5000 square miles with varying degrees of intensity. In the Androscoggin River Area approximately 200 miles of traverse have been surveyed and about 175 test-readings taken. Existing conditions did not warrant more extensive surveys. The readings taken cover a range in elevation from 200 feet above mean sea-level to 3000 feet above mean sea-level.

There is a growing interest in the eastern part of Maine in opening up new territory to snow-surveying and the writer is assisting in this extension work. There is also a general and lively interest in the results obtained on the part of the general public.

New York (E. S. Cullings)

In the Adirondacks, the past winter has approached normal conditions. There has been one short period of extreme cold and one warm period early in January, during which a considerable part of the accumulated snow was melted.

At this date the snow cover appears to be a little below normal in the northwestern part of the Adirondacks and somewhat above normal in the southern part. There is little frost in the ground. Reports indicate from 20 to 25 inches of ice in the Adirondack lakes.

The usual snow-survey was conducted in the Oswegatchie, Raquette, Black, Mohawk, Oneida, and Sacandaga (Hudson) watersheds.

The survey was the cooperative work of the State Department of Public Works (Utica Office), Hudson River Regulating District, Black River Regulating District, and Niagara-Hudson Power Corporation (Central Division).

Northern Continental Divide (G. A. Hathaway)

Relative to snow-surveys in the upper Missouri Basin, the work of computing precipitation, runoff, and snow normals has been completed for Fort Peck, and several points on the Main Stream, as well as for ten tributary basins. The normal for the water-content for the snow in storage on March 1 is, of course, rather approximate but it is felt that the figures will be accurate enough for the time being. The precipitation and runoff normals were based on records over the period 1910 to 1934, inclusive, and are for the climatic, or hydrographic year (October 1 to September 30 of the following year).

Several new courses have been established, mostly at higher elevations, and in addition there are three key stations at which snow-surveys are made on the first of each month from January to May, inclusive. These key stations are at Marias Pass; in the vicinity of Rimini, a small town located near Helena, Montana; and at Hebgen Dam in the headwaters of the Madison River. Snow-surveys were made at these stations on the first of January, February, and March of this year.

During April 1 to July 31, 1934, the runoff of the Missouri River at the Fort Peck Dam was 61 per cent of normal. The precipitation for the same period was 87 per cent of normal, with an accumulated departure of temperature of 4° above normal. The 1934 weighted water-content of snow in storage on March 1 was 66 per cent of normal.

On the same basis the weighted water-content of snow in storage in the Missouri River Drainage Basin above the Fort Peck Dam on March 1, 1935, was 57 per cent of normal. The trend of precipitation from October 1, 1934, to March 1, 1935, over the same area is 76 per cent of normal. With a water-content of the snow in storage on March 1, 1935, equal to 57 per cent of normal, an estimate has been made of the probable runoff of the Missouri River at the Fort Peck Dam during the period April 1 to July 31, 1935, under the assumption that the trend of precipitation would continue at the rate of approximately 75 per cent of normal, and that the accumulated departure of temperature would remain from 3° to 4° above normal. Results of the study indicate that a runoff of 2,520,000 acre-feet can be expected over the period April 1 to July 31, 1935. A runoff of 2,520,000 acre-feet for the period April 1 to July 31, inclusive, is about 55 per cent of the normal flow of the stream for the same period

(based on stream-flow records from 1910 to 1934, inclusive).

The actual field-work, in connection with the snow-surveys, has been accomplished under the supervision of W. A. Lamb, District Engineer of the United States Geological Survey at Helena, Montana, with funds supplied by the Division Engineer's Office, Missouri River Division, Kansas City, Missouri. All office studies have been made in the Division Engineer's Office. R. C. Moore, Colonel, Corps of Engineers, United States Army, is the Division Engineer in charge of the Missouri River Division.

Southern Continental Divide (E. B. Debler)

Montrose W. Hayes, in charge of the River and Flood Division of the United States Weather Bureau, reports that the United States Bureau of Reclamation has outlined a snow-survey system for the entire Colorado Basin and is seeking cooperation in putting it into effect. Owing to the prevalence of snowslides in the Continental Divide, especially in the San Juan Basin, snow-courses must be laid out with reference to accessibility under all conditions of weather.

Eastern Great Basin (G. D. Clyde)

Utah now has a state-wide network of snow-courses--85 in number. These courses, for the most part, are located above 8000 feet elevation. The courses are surveyed by various cooperating agencies consisting for the most part of United States Forest Rangers, United States Park Rangers, irrigation-company officials, and officials of municipalities. The work is conducted under an informal cooperative agreement between the Utah Agricultural Experiment Station, the United States Forest Service, the United States Weather Bureau, and the Utah State Engineer.

The drought of 1934 brought surveying in Utah to a focus. Prior to that time the work was done largely by the Utah Agricultural Experiment Station. The water-supply forecast for 1934, prepared by the Experiment Station, was the basis upon which the Governor made his appeal to Washington for drought relief, and as a result of this appeal early in the season a water-conservation program was developed and, with the aid of Federal drought-relief funds, supplementary water-supplies were developed to the extent of approximately ten per cent of the normal total water-supply. It is estimated that there resulted from this water-conservation and drought-relief program, which was based entirely upon advance information with respect to water-supply resulting from snow-surveys, a saving in crops alone to the State of approximately $5,000,000.

With the results of the season of 1934 in mind, the State Engineer requested an extension of this work and through his efforts the State appropriated $500 to the execution of the work this winter. The Governor has placed in his budget $1000 per annum for the continuation of snow-surveys and in all probability this fund will be available. With the additional funds it is proposed to extend and refine the work and improve equipment. It is believed that it would be desirable to clear many of the snow-courses, erect shelter-cabins, and provide additional equipment to snow-surveyors.

Due to many emergency duties during the past year, research work has suffered. However, some information is being collected this winter on the effect of temperatures on the high watersheds and the effect of a deficit in low snow-cover on the yield from the high elevations.

Western Great Basin (H. P. Boardman)

In Nevada state cooperation has been restored by the passing of a legislative appropriation of $1000 for snow-surveying and $1500 for stream-gaging. This sum will apply to the biennium beginning July 1.

Snow-surveys in the Sierra Nevada the present season were supported by a Federal Emergency Relief Administration allotment from unexpended drought-relief funds. A heavy storm in early April has increased the snow cover to 80 per cent and upwards of its April 1 normal.

The snow-surveys in the Humboldt Basin were supported as usual by the State Engineer from funds for the distribution of Humboldt waters and an appropriation by the Nevada Agricultural Experiment Station for research in improving stream-flow forecasting. The snow-surveys themselves and test-well measurements were made under the direction of the United States Forest Service, which has now offered to install shelter-cabins for snow survey-parties throughout the Basin.

Although this season's snow cover was 73.7 per cent of normal, the low water-table combined with the alluvial stream-bed and numerous dams will probably reduce the downstream runoff to 25 per cent of normal.

Snow-survey courses in this Basin are now approaching ideal in location and number. Snow-surveys are being conducted monthly at key stations in addition to the general annual survey March 1. However, fear of snowslides during the mild weather early in April prevented the April 1 survey at the high-level course at 9000 feet in the Ruby Range.

Through the generosity of the Experiment Station formal cooperation in stream-gaging was

maintained between the State and the United States Geological Survey during the lapse of appropriation by the Legislature.

George Hardman, in charge of the Division of Irrigation in the Experiment Station, has joined cooperatively in the studies of snow cover and stream-flow.

California (H. M. Stafford)

The status of snow-surveying in California during the past year has been practically the same as reported for the previous year 1933-34. Since July 1, 1933, the State has had no appropriation for continuing its cooperative work and the surveys that have been made have been carried on by agencies which were formerly cooperating with the State. Although some of these have faithfully continued the program originally set up, many others have only partially continued the program or have completely abandoned it. There is a great need, therefore, for a resumption of the State's supervision, correlation, and financial assistance if the successful beginning and program of the initial four-years' effort up to 1933 are not to be gradually lost. State equipment has remained in the field with the cooperating agencies but there is a considerable need for replacements and repairs and new equipment for extensions; also there are many locations where shelter-cabins should be constructed. It is unlikely that any of this work will be done unless the State cooperation is resumed. The irrigation-interests and others concerned in the snow-surveys are sponsoring a movement to have the State cooperation on this work resumed and a bill to accomplish this is pending at the present session of the California Legislature. Whether or not this is approved, it seems almost certain that the project of snow-surveys in California is due for a decided stimulation and expansion at such time as the Central Valley Water Project becomes an assured fact. This project will require the coordinated regulation of the stream-flow for many and varied forms of utilization and the data of snow-surveys are practically indispensable to efficient regulation of this character.

The estimated seasonal runoff from the basins covering the western slope of the Sierra Nevada, as based on snow cover, precipitation, and all known factors April 1, was from 80 to 90 per cent of normal. This should be materially increased by the semi-flood storm of early April.

Southwest (H. S. Colton, Director, Museum of Northern Arizona)

Gages are maintained at Flagstaff at the Laboratory of the Museum of Northern Arizona, altitude 7100 feet, another gage in the Coconino Divide on the east side of the San Francisco Peaks, and three other gages down to an altitude of 500 feet. There is also a gage at 10,800 feet in the Fremont Saddle in the San Francisco Peaks. This indicates the scope of the work that is being done in the winter at the Museum of Northern Arizona.

Pacific Northwest, especially Lower Columbia (J. H. Ryan)

With the exception of a winter survey on two courses on the Umatilla River watershed, no information regarding snow-conditions in Oregon was gathered in 1934, and at the time this appeared to be the end of the attempt by the Water Resources Department to build up a system of snow-surveys within the State.

There is a decided change for the better, however, in the attitude displayed this year. With agricultural products finding better markets, and, in turn, tax collections showing a healthy percentage of increase, the irrigation-districts and county courts are willing to spend a little money, although not very much, for data regarding the probable runoff this coming summer.

In the Rogue River Basin the surveys are being financed partly by the Oregon Agricultural Experiment Station. In the Grande Ronde Basin the work is being handled through cooperation with the State Planning officer of the State Emergency Relief Administration in connection with the work of that agency in sinking wells and developing springs in the arid areas. The irrigation-districts and counties are financing the surveys in all other drainage-basins except that of Powder River, where no surveys were made in January. The State Engineer is hopeful of getting surveys there this spring.

M. R. Lewis, Irrigation and Drainage Engineer on the staff of the Oregon Agricultural Experiment Station at Corvallis, Oregon, has been displaying considerable interest in the snow-surveys, and is responsible for the cooperation of the Experiment Station in the surveys in the Rogue River Basin.

Cooperation is being given in so far as possible with the United States Army Corps of Engineers in charge of Bonneville Dam, looking towards the establishment of a snow-survey system on the Upper Columbia River Watershed. All the Oregon stations which are on tributaries of the Snake River are in line with their plan for a system of surveys which will eventually cover the headwaters of the main tributaries to the Columbia River.

While the prospects for water this year are considerably better than they were in 1934, there is still much to be desired.

Pacific Northwest, especially Upper Columbia (E. H. Collins)

Major H. S. Skerry, Executive Officer of Corps of Army Engineers in charge of the Bonneville Dam Section of the Columbia River, writes for the District Engineer as follows: "Consideration is now being given by this Office and other agencies to the use of snow-surveys in connection with the prediction of stream-flow in the Columbia River. Further development along this line may require the establishment of definite locations for obtaining and utilizing such data. Nothing tangible, however, has developed at the present time."

British America, British Columbia (J. C. MacDonald, Comptroller of Water Rights)

With reference to your mid-year letter of February 15, 1935, I note that the United States Army Corps of Engineers are requesting information on snow-surveys applicable to regulation of the Bonneville Dam. In this connection you may be interested to know that we established a number of snow-courses in British Columbia last summer, and that seven of these lie in the Upper Columbia Drainage. I enclose a map showing the location of these courses.

British America (Mathew Balls)

I was very pleased to receive your letter of March 23 and to note that British Columbia has established snow-survey courses in the Upper Columbia Valley. In this connection E. Davis, Chief Engineer of the British Columbia Water Rights Branch, with whom I had discussed snow-surveying about three years ago, wrote to me last year for information concerning the results of our St. Maurice snow-surveys and for suggestions concerning the inauguration of snow-surveys in British Columbia. I sent Mr. Davis a brief memorandum on the subject and suggested particular locations for snow-courses on three important watersheds including the Upper Columbia Basin. It is therefore interesting to me that courses have been established in the latter Basin and I shall be pleased to follow the progress of the British Columbia snow-surveys and to compare notes as to results from time to time.

As to the rest of Canada and Newfoundland there seems little to report. I am informed that the Federal Government is continuing the snow-surveys at the headwaters of the St. Mary and Winnipeg rivers, along the lines previously reported. Among private companies only the Gatineau Power Company (Gatineau River) and Shawinigan Water and Power Company (St. Maurice River) are carrying on snow-surveys.

I had an opportunity last summer of discussing snow-surveys with Mr. Blue who has charge of this work for Gatineau Power Company. He informed me at that time that they had been unable to arrive at any definite conclusions as to the value of the surveys but would continue them for some years in the hope of establishing a relationship between water-content of snow cover and the spring runoff.

No articles relating to the hydrology of snow have come to my attention during the past year.

Conservation (Joseph Kittredge, Jr.)

The project of the California Agricultural Experiment Station on the influence of different kinds of forest-cover on the accumulation, density, evaporation, and melting of snow at elevations between 5000 and 6300 feet in Tuolumne County is being continued for the second winter. Preliminary computations of the 1934 record indicate that the interception of snowfall by the crowns of the trees, expressed as percentages on the basis of water-equivalents of snow, varied from 58 per cent for dense immature white fir to about 25 per cent for a stand of mixed conifers from which more than half the timber had been cut. Stands of Ponderosa pine, mixed conifer uncut, and red fir gave intermediate values. The averages are based on snow-board records at ten mechanically-spaced sampling points in each stand as compared with the amounts recorded in openings within or immediately adjacent to the stand. Large variations were found at individual sampling points depending upon their location with respect to the crowns of individual trees.

Small evaporation-pans filled with snow and set flush with the snow-surface, and provided with holes for drainage and measurement of water from melting, showed gains rather than losses during March when the snow had begun to disappear in spots. Apparently during this period condensation on the snow-crystals exceeded the loss by evaporation during both day and night periods. The gain or excess of condensation over evaporation amounted on the average to about 0.01 inch of water per day.

Ice (Howard T. Barnes)

Some little progress has been made in the work of cataloging the texts on ice. The following titles in the section of "Current publications" have been noteworthy.

Equipment (S. P. Fergusson)

I have not been able to work on new or special apparatus for snow-surveying or hydrology since last year; our problems of measurement in this region are simpler than is the case in

the Sierras and Rockies, where the depth is so much greater, and there is little opportunity for field-work trying new devices. I noted in your Bulletin "Proceedings of the Western Interstate Snow-Survey Conference" that the Utah people have already a tubular spring-balance satisfactory for their use and it would seem that this could be used as a starting point in the design of one of larger capacity for the California-Nevada conditions--probably with a saving of time and cost.

Arctic (W. H. Hobbs)

Dr. Hobbs has been retired at the University of Michigan, but refuses to join the "dodo" class. However, the present winter he is making a tour of the far Southwest afar from his library which has served as a source for "Current publications."

Antarctic (L. M. Gould)

I had really expected to have some contribution of my own for your annual report this year. But my rather lengthy article on the Ross Shelf Ice, with a considerable amount of material on precipitation, ablation, and so on, has not yet been published. It is in the hands of the Geological Society of America, and you may be sure a copy will be sent you immediately it is available.

I am suffering the same handicap as last year in the matter of keeping up to date on bibliographical material. I do not believe I shall have to make this excuse another year, for we are making great strides in our library at Carleton College, and I hope to have access to sources of information on the lines of my own interest before another year has passed.

Publicity

The Questionnaire on Snow is still under analysis. An address list of those interested in snow-surveying is slowly being compiled. Progress has been made as far west as the Continental Divide. Because of inquiries for information on snow, Engineering News-Record has requested that two articles be prepared covering the results of the Questionnaire. The completion of this work will now be given major attention and a formal address list will be published.

The list of colleges and schools in the United States and Canada giving courses in Hydrology, with the type of courses given by each, has now been sent to these institutions for verification. Stimulation and even rivalry have resulted. Professor Thorndike Saville of New York University has been asked to cooperate in making the list fully standard and reliable.

Publicity for snow-surveyors themselves has been given in an unsought article in Westways (November 1934) on "Unsung heroes of the Sierra snow-surveys." The "unsung" heroines are the wives who send their husbands forth and wait. This article is the instinctive reaction to the Marine Corps spirit shown by the surveyor.

The Proceedings of the Western Interstate Snow-Survey Conference of the past year have been published through the generosity of the Division of Hydrology with which the Conference was permitted to affiliate at the Pacific Coast Meeting.

The large monograph on "Snow-surveying with reference to forecasting stream-flow: Its problems and their present phases" has been sent to Washington for consideration by the United States Senate as a possible Senate Document. Its publication has received the approval of the Chairman of the National Resources Board as fundamental to the measurements of water-resources.

Two other articles by the Committee Chairman are now in press. These are "Principles of snow-surveying as applied to forecasting stream-flow" in the Journal of Agricultural Research and "Snow-surveys as an aid to flood-forecast and control" in Engineering News-Record.

Radio publicity is hastening its pace. Local broadcasts of snow cover and probable runoff have been given by Professor G. D. Clyde from Salt Lake City, Utah, and Professor H. P. Boardman from Reno, Nevada. In connection with the Farm and Home Hour broadcast sent from San Francisco to the Western States, the Nevada Agricultural Experiment Station has furnished radio talks on "Forecasting the runoff of the Columbia River Basin," "Snow-conditions in the Central Sierra, the Feather River Basin, and in the Humboldt Basin of Nevada, February 1," and "Snow-cover conditions April 1 over the Western United States." This latter broadcast has now been enlarged to include the snow-cover conditions from the Continental Divide to the Pacific Coast and will be given early in each month from February to April or May.

The continuing calls for information and conference both from home and abroad reemphasize the value of snow-studies. A standard national system of snow-surveying is even now being developed and the practical aspects of snow have now a place in European hydrology.

Popular newspaper articles have been published on "Normals," "Snow-records at Blue Lakes," and "Snow-survey work at Blue Lakes Course." A service club lecture was requested in the Humboldt Basin to interpret the annual snow-survey data and forecast. This was given by the Supervising Water Commissioner of that Basin. Thus gradually and almost imperceptibly regions dependent upon irrigation are growing snow-minded.

Western Interstate Snow-Survey Conference

By mutual consent of the American Meteorological Society and the Section of Hydrology, the Western Interstate Snow-Survey Conference met in affiliation with the latter at the Pacific Coast session of the American Association for the Advancement of Science held at Berkeley, California, the week ending June 17, 1934. The meeting was attended as numerously as had been the previous meeting held in Nevada, but this time mainly by technicians from power- and irrigation-districts and the United States Forest Service. The program was as follows: (1) Temperature-divergences between valley and mountain stations, George V. Sager; (2) Evaporation at high altitudes, J. E. Church; (3) Flow-characteristics of glacier-fed and snow-fed streams, Richard G. Tyler; (4) Relationship of degree-days above freezing to runoff, E. H. Collins; (5) Improvements in forecasting the flow of the Humboldt River, Nevada, Carl Elges, Jr.; (6) Improvements in snow-surveying apparatus, James E. Jones; and (7) The Stevens annual snow- and rain-recorder, J. C. Stevens. The following Executive Committee was chosen for 1934-35: James E. Jones (Chairman), City of Los Angeles Department of Water and Power, Los Angeles, California; J. E. Church, Meteorologist, Nevada Agricultural Experiment Station, Reno, Nevada; George D. Clyde, Utah Agricultural Experiment Station, Logan, Utah; Joseph Kittredge, Jr., Professor of Forestry, University of California, Berkeley, California; and Harlow M. Stafford, Supervising Hydraulic Engineer, Division of Water Resources, Sacramento, California.

The Chairman is seeking greater intimacy and interchange of views through a detailed questionnaire to all workers in the field of snow-surveying. Approximately 80 answers to the questionnaire have been received.

Owing to the postponement of the next Western meeting of the Section of Hydrology until next winter, the Snow-Survey Conference is confronted with the problem of setting a date for the annual meeting. The snow-surveyors prefer the slack period of midsummer, the hydraulic engineers midwinter. A joint session of the three organizations of meteorology, hydrology, and snow in connection with the American Association would be ideal. However, the work of the Snow-Survey Conference is more closely allied with the Section of Hydrology which in addition has offered close affiliation in combined meetings and publications. (The Executive Committee has finally decided to request affiliation with the Section of Hydrology.)

Cooperation

Cooperation has become the spirit of the year. More agencies are assisting in snow-surveying and likewise more assistance from snow-surveying is being sought. Only the new developments are recounted. Most prominent among those taking active part in snow-surveying is the Division of Irrigation of the Bureau of Agricultural Engineering. Through an appropriation from the United States Government the Division is making plans for increasing snow-survey courses and shelter-cabin facilities in the western States. Those having charge of snow-survey work have been requested to send suggestions for improvement of their own courses and for establishment of new courses, as well as improvement of and building of new shelter-cabins, to James C. Marr of the Division. Mr. Marr and Professor George D. Clyde of the Utah Agricultural Experiment Station have made a special trip to confer with snow-survey leaders concerning this work.

In Utah the State has assumed an active share in snow-surveying.

In eastern Nevada the United States Forest Service is not only making practically all of the snow-surveys but has even offered to provide shelter-cabins at all necessary points to assure access to the courses despite snow- and weather-conditions.

In western Nevada the Federal Emergency Relief Administration granted approximately $1000 surplus funds from drought relief for the April 1 snow-surveys in the Sierra Nevada.

At the Nevada Agricultural Experiment Station the department of irrigation has united with the department of meteorology in stream-flow forecasting.

The United States Coast and Geodetic Survey and the United States Geological Survey have placed all available data, including those unpublished, at the service of this Station for the

purpose of creating a provisional topographic map of the Upper Humboldt Basin until comprehensive detail surveys can be completed.

To prevent cooperative stream-flow measurements by Nevada and the Water Resources Branch of the United States Geological Survey from lapsing during the past biennium, the Nevada Experiment Station provided sufficient cooperative funds to maintain the formal relationship and thus make it possible for the Geological Survey to spend emergency stream-gaging funds in the State.

The statisticians of the Division of Crop and Livestock Estimates of the United States Department of Agriculture at Denver, Salt Lake City, and Oakland have requested forecasts of seasonal stream-flow as a basis for granting loans on the current farm and range output.

Finally, the Western Unit of Radio Service of the United States Department of Agriculture, at the suggestion of the Nevada Agricultural Extension Service, has inaugurated a monthly forecast of snow-conditions for the entire region west of the Continental Divide. This broadcast, though directed from the Nevada Agricultural Experiment Station, is made possible by the generous cooperation of State Engineers, Experiment Stations, the United States Forest and Park Services, and the United States Weather Bureau of the various states, including also water- and power-organizations and the press. The generosity of the press has been expressed in procuring special telegraphic data, in publishing bulletins, and even in printing forecasts in separate form for general distribution.

Of greatest interest was the recent trip of Montrose W. Hayes, in charge of the River and Flood Division of the United States Weather Bureau, to seek points of cooperation with the Western States. A conference of approximately 40 representing the snow interests of Nevada met with him at the Agricultural Experiment Station at Reno. A great diversity of method and variety of leadership throughout the West were revealed and the need and feasibility of standardization and unified leadership were stressed.

The Proceedings of this Conference were prepared for circulation by the Station as a basis for report to the Weather Bureau at Washington and other national agencies. At the suggestion of Mr. Hayes, a plan of national organization was later prepared by the writer, who gladly acted in his capacity as Chairman of the Committee on Snow.

National snow-survey direction

The changing attitudes of the West toward the vital necessity of snow-surveying and intensive stream-gaging was recently expressed by the terse statement of Governor Kirman of Nevada in his initial message to the Legislature:

"The extreme drought of 1934, coupled with the steadily declining precipitation of the past several years, emphasizes the importance of increased attention to records, forecasting, and distribution of the available water-supply. Every possible aid should be given to proposals for upstream-storage of water on the rivers of our State, as well as other storage- and construction-projects beneficial to our irrigation-interests, to insure our farmers or ranchers of water for irrigation-purposes when the same is needed and can be best utilized."

A similar sentiment but with emphasis upon National rather than State direction was expressed at the annual meeting of the Pacific Coast Section of the American Society of Agricultural Engineers at Corvallis, Oregon. The resolution was as follows:

"WHEREAS, The low-water flow of the major streams of the West is dependent on the snow-cover in the high mountain watershed, and

"WHEREAS, Foreknowledge of low-water flow would be of great assistance in planning farm operation of irrigation and power storage-reservoirs, and for flood-control and flood-damage abatement, and

"WHEREAS, It has been demonstrated in several localities that snow-surveys can be used in predicting low-water flow, and

"WHEREAS, General application of the snow-survey method waits upon a coordination of the results secured in these several localities by a national organization having the personnel and equipment to make the necessary field and office studies, therefore, be it

"RESOLVED by the Pacific Coast Section of the American Society of Agricultural Engineers, that the Secretary of Agriculture in cooperation with appropriate agencies be requested and empowered to make comprehensive snow-surveys in the several western states together with adequate studies of the methods and equipment."

Similar but more urgent resolutions were passed by the National Reclamation Association and the Association of Western State Engineers at Salt Lake City. These resolutions were directed to the Secretary of Agriculture possibly because of the present tendency to seek relief from the National Government. The resolution of the Reclamation Association in detail is as follows:

"WHEREAS, The agricultural interests of the West are vitally concerned with the quantity and location of winter snowfall, which determines in large measure the following season's irrigation water-supply, and

"WHEREAS, The practicability and value of snow-surveys have been demonstrated, but coordinated plans of predicting stream-flow from snow-survey data have not been made, and

"WHEREAS, Reliable forecasts of stream-runoff prior to the flood-flow season would afford warning of impending floods and of water-shortages, and thus make possible the taking of measures to prevent flood-damage, and to adjust agricultural programs to meet expected water-shortages, with material benefit to agriculture under irrigation, and

"WHEREAS, The United States Department of Agriculture is fitted to cope with the agricultural and engineering problems involved, now, therefore, be it

"RESOLVED, That the National Reclamation Association, convened at Salt Lake City this eighth day of December, 1934, respectfully requests the Secretary of Agriculture or other authorized Federal agencies to authorize a coordinated plan of snow-surveys on important streams, with sufficient funds to accomplish the purpose effectively, and be it further

"RESOLVED, That a copy of this resolution be sent to the Congressional Delegations of the thirteen Western States."

The resolution of the Western State Engineers emphasizes the need of foreknowledge of water to avoid planting crops which cannot be matured. Its details are as follows:

"WHEREAS, The agriculture of the Western States depends primarily upon irrigation, and the irrigation water-supply is derived very largely from the melting of snow, and

"WHEREAS, Great waste of money and labor in the planting of crops in recent years has resulted from inadequacy of water-supplies to bring them to maturity, and

"WHEREAS, Adequate snow-survey data would make possible the forecasting of seasonal water-supplies and thus minimize these losses, and

"WHEREAS, Snow-surveys and forecasts will materially facilitate the apportionment and distribution of water-supplies and thereby lessen disputes among water-users, and

"WHEREAS, The questions involved are agricultural and engineering, now, therefore, be it

"RESOLVED by the Association of Western State Engineers, that the Secretary of Agriculture or other proper Federal agencies be directed to undertake comprehensive snow-survey investigations in the watersheds of Western streams to the end that reliable forecasts may be made of the seasonal runoff and the distress resulting from floods and droughts reduced accordingly, and be it further

"RESOLVED, That a copy of this resolution be sent to the Congressional Delegation of each of the Western States."

However, at the Institute of Irrigation Agriculture meeting held in Los Angeles, a strong resolution was adopted recommending the resumption of abandoned snow-survey work in California and the extension of similar work to the drainage-basins farther west.

Fortunately, the National Resources Board had already through its Water Resources Section recommended the collection of basic data and that "more attention be given to measurements of depths of snow in certain regions." In interpreting this recommendation, the Chairman of the National Resources Boerd wrote as follows:

"The Water Planning Committee in its report (p. 286) has strongly recommended the more extended and intensive accumulation of hydrologic data, and, while precipitation was not specifically mentioned, it was distinctly in the mind of the Committee in its reference to 'Surveys of water-resources.' It is hoped that this recommendation will be followed by arrangements to carry them into effect, in which case all pertinent agencies of Government and scientific consultation will be brought into cooperative association, and, where practicable, utilized in the execution of the resultant plan."

The spontaneous demand for snow-surveying, the willingness of the Government to assist in its financing, and the wide cooperative interest in its maintenance caused the Chairman of the Committee on Snow to write Mr. Hayes, representative of the United States Weather Bureau, as follows:

"After some thought I have outlined the following plan of organization of snow-surveys. It

seeks to include all interests engaged in snow-surveying and so to avoid all rivalry and overlapping. It also tries to make use of funds possibly available from the National Resources Board. It leaves leadership to those most vitally interested. However, it seeks centralized direction and standardization. It can be put into active operation as soon as the National Resources Board is prepared to carry out its recommendation. It might be well also to present it to the various organizations that have passed resolutions urging the Secretary of Agriculture to organize snow-surveys. Above all things else we need concerted action in order that all future advance may be consistent and steadfast."

Time thus far has been too brief for many opinions. But to avoid delay the plan with slight additions has been submitted to Professor Thorndike Saville, Consultant to the Water Resources Section of the National Resources Board. It is also inserted below in this report for possible consideration and recommendation by the American Geophysical Union.

A general plan of organization of national, regional, and state snow-surveys and stream-flow forecasting

(Proposed by the Chairman of the Committee on Snow of the American Geophysical Union to Federal, State, and private organizations for consideration and possible approval)

The name, organization, and purposes are as follows:

National Water Resources Board--National Water Resources Board to be composed of representatives of the Bureaus or Commissions of Weather, Geology, Forests, National Parks, Agricultural Engineering, Reclamation, Soils Irrigation, Power, Navigation; State organizations, where states are engaged in snow-surveying; and civilian experts in hydrology.

Divisions of interest to be apportioned somewhat as follows:

(1) Meteorology--United States Weather Bureau, precipitation- and temperature-stations, key weather stations
(2) Snow-surveying--United States Weather Bureau, United States Forest Service, National Park Service, United States Geological Survey, Bureau of Agricultural Engineering, United States Bureau of Reclamation, United States Army Engineers (navigation), and State cooperative snow-surveys
(3) Stream-flow gaging--United States Geological Survey (Water Resources Branch), United States Weather Bureau (river heights), United States Army Engineers (navigation)
(4) Underground waters--United States Geological Survey
(5) Evaporation, transpiration, percolation--United States Weather Bureau, United States Forest Service, United States Division of Irrigation Engineering
(6) Floods--United States Weather Bureau, United States Army Engineers
(7) Forecasts and broadcasts--United States Weather Bureau, United States Division of Irrigation Engineering, United States Power Commission (?), United States Bureau of Reclamation (?), United States Army Engineers (navigation), State cooperative snow-survey organizations
(8) Publication of data--United States Weather Bureau, United States Geological Survey
(9) Investigations, research--All boards, research to be conducted by the boards or combination of boards most competent and interested

This National Board shall establish policies and standards, and shall perform active work wherever necessary to perfect a uniform forecast-service. However, where possible or where organized forecasting now exists, it shall be the policy of the Board to advise and cooperate.

State or regional water-resources boards--Supplementary to the National Board shall be State or regional water-resources boards in closer touch with actual local conditions. Regional boards shall be organized for basins that are obviously interstate or national. Such are the Columbia, Colorado, Missouri, St. Lawrence, etc.

These boards should consist of the State or regional representatives of the National bureaus or commissions represented in the National Water Resources Board and representatives of such State and local organizations as are interested in the conservation and application of water. Such are the State engineers, irrigation-engineers, power-engineers, watermasters, Experiment Station specialists, State water-departments, water-districts, and power-companies. These State or regional boards should perform the actual work from snow-surveying to forecasting.

Cooperation--Wherever possible, financial and other cooperation should be established and maintained between the water-districts and power-companies and the State or region. In like manner State or regional cooperation should be maintained with the Federal Government. Thus, sharing

in the direction and maintenance of the surveys should increase the public interest and responsibility. However, National or State service should not be withheld from any unit because of failure to cooperate.

Research--Experimental stations or projects should be maintained wherever the material is most abundant or the personnel for the particular task most efficient. Thus, (1) underground flow might well be studied in the Owens Valley, (2) desert streams in the Great Basin, (3) effect of chinooks in Montana.

Direction--The organization of the National Water Resources Board may well be placed at present under the National Resources Board, which will doubtless have the funds necessary for such work. But where possible the leadership already active in some of the states should be maintained except that wider Federal cooperation should be afforded.

The main purpose ever to be kept in mind is the cooperative employment of all agencies interested in the work and the avoidance of rivalry and overlapping. Actual leadership in both National and local boards will depend upon intensity of interest and adaptability to the work in hand.

Research

Research has been active in many lines.

(1) Evaporation-studies are being continued by the State Electricity Commission of Victoria, Australia, in connection with runoff under the leadership of L. T. Guy and by the Department of Forestry of the University of California in the study of conservation of snow under the leadership of Professor Joseph Kittredge, Jr. The Nevada Agricultural Experiment Station under the leadership of the writer is continuing the analysis of evaporation-data collected in the Sierra Nevada and central western Greenland to determine the relationship of Alpine and Arctic climate to evaporation.

(2) Investigation is being conducted in long-time normals or trends which reach back far beyond precipitation and stream-flow measurements. Among these are: Changes in lake levels in the Great Basin Area by S. T. Harding, Professor of Irrigation, University of California; precipitation and tree-growth in the Harney Basin, Oregon, by L. T. Jessup, United States Bureau of Agricultural Engineering, and T. W. Robinson of the United States Geological Survey; and precipitation-trends in the western portion of the Great Basin in terms of tree-growth by George Hardman, in charge of the Department of Irrigation, Nevada Agricultural Experiment Station. These studies are valuable not only in the expansion of present precipitation and runoff normals but in land utilization and adjustment.

(3) The seasonal variation in the water-table in the Humboldt Basin, Nevada, is being studied as a possible correction-index to apply to the snow-cover percentage in determining the net percentage of runoff to be expected. This study is a broad cooperative project directed by the Nevada Agricultural Experiment Station and other State and Federal agencies.

(4) The relation of snow-cover to the relative amount of summer precipitation to be expected in its lee is the subject of research by O. W. Monson, Irrigation Engineer, Montana Agricultural Experiment Station, in connection with the precipitation phenomena in the Central Sierra and on the Pacific Coast.

(5) The relation between precipitation at mountain-valley stations and adjacent snow-survey courses and the coordination of snow-survey measurements to a common date are being investigated by H. P. Boardman, Professor of Civil Engineering, University of Nevada, and Chairman of the Nevada Cooperative Snow-Surveys.

(6) Tests are being made of the possibility of constructing a snow-sampler of aluminum alloy adapted to the varying depth of snow-cover found in the Sierra Nevada and Cascades. This work is being done by Frederick and Walter Herz for the Nevada Agricultural Experiment Station at the suggestion of the Western Interstate Snow-Survey Conference.

Bibliography of ice and snow

The compilation of a bibliography of ice and snow is now advancing at a faster pace. Professor Howard T. Barnes of the Committee is continuing his compilation and annotation of articles and books on ice. By aid of Federal Emergency Relief Administration student-relief funds,

Professor H. P. Boardman is excerpting engineering literature. With similar funds the writer is copying a bibliographic list loaned by Dr. Charles F. Brooks, Director of the Blue Hill Observatory.

The International Association of Scientific Hydrology and the Hydrologic Conference of the Baltic States are generously forwarding their bulletins and separates.

International organization

International cooperation in snow is slowly, yet steadily, progressing with the interchange of letters and publications.

The reports of the 1933 meetings of both the International Association of Scientific Hydrology at Lisbon and the Hydrologic Conference of the Baltic States at Leningrad have finally arrived, and are given in outline with pertinent articles under the section "Current publications."

The minutes of the discussion in the International Association regarding the feasibility of creating a Commission of Snow are quoted in full because of the diversity of interest in measurements of snow as between America and Europe and Europe's generous appreciation of the International character of the work (Association Internationale d'Hydrologie Scientifique, Cinquième Assemblée Generale à Lisbonne, Sept. 1934, p. 267; translated by S. B. Doten):

"Commission of Snow--The chair was occupied by M. Smetana who asked that M. Mercanton express his opinion on the American proposal concerning the Committee on Snow.

"M. Mercanton pointed out that snow-measurement is a science to which the Americans have devoted great activity. Several methods have been applied by them; he mentioned in particular the utilization of the Church snow-sampler.

"The problem which presented itself was to learn whether the International Hydrological Association considered the creation of such a section a goal sufficiently international (in character).

"The requirements of Eruope and those of America, on the subject of snow, are not really identical, but M. Mercanton thought that in principle the Association might be favorable to such a Committee, always on the condition that the Committee work specifically from the point of view of hydrology. It should have, for example, the problem of studying the reserves of water held by the snow.

"This resulted in a statement transmitted in the course of the meeting to the effect that there was a perfect agreement between the proposal of the Americans and the opinion of M. Mercanton up to the point where it dealt with the establishment of a forecast of stream-flow after the melting of snow.

"Certain members, having voiced the fear that the International Meteorological Association might consider a Committee on Snow an encroachment on its field of work, asked that the establishment of the Committee be deferred until after agreement with the Meteorologists.

"The President of the International Meteorological Association, present in the meeting, saw no difficulty in such an undertaking and on the contrary favored it. He thought that it should be separated from the Glacier Commission inasmuch as it should deal with the forecasting of the rise in the level of lakes.

"The President resumed the discussion and made it known that there are in certain countries snow-fields without glaciers, and that in consequence the study of snow in connection with the rise of streams and lakes should be undertaken outside the Glacier Commission.

"The Americans are much to be praised for the activity which they have shown in this section of the science and the President thought that by assigning the Presidency to M. Church, that Committee would be able to develop its own detailed program for the next meeting in 1936.

"It was decided to add a meteorologist, M. Eredia, and a provisional secretary, M. Mercanton, to cooperate with M. Church in forming the program of the new Committee."

The first appointment of the initial members was plainly to assure broad relationships with the correlated sciences of meteorology and glaciology, for Professor Eredia is the Vice-President of the International Meteorological Association and Professor Mercanton is Secretary of the International Commission of Glaciers.

These broad relationships are being continued in other members already appointed to the Commission of Snow and the field has been widened to include the hydrology of snow and seasonal ice, including also runoff from glaciers, a subject akin to runoff from snow. In this way the hydrological interests of America and glacier-watered countries will be brought closer together.

The full personnel, field of interests, and program for the 1936 meeting should be completed by the next annual meeting of the American Geophysical Union.

The International Congress of Ice

The International Congress of Ice which also embraces snow in a minor way has been formally authorized by the officials of the next Hydrologic Conference of the Baltic States. But because Finland feels that the responsibility for the Baltic Conference will be heavy, the United States of the Soviet Republic have gladly offered to act as host to the Congress of Ice.

Correspondence is now under way regarding the affiliation of the International Congress of Ice with both the Hydrologic Conference of the Baltic States and the International Association of Scientific Hydrology. This will give the Congress greater international character and expand the field to include ice and snow in their broadest joint aspects.

An endeavor also is being made to have the meetings of the three organizations so arranged that it will be possible for foreign delegates to go readily and without loss of time from one to the other. Since September is the month and the International Association has already accepted Edinburgh, the Baltic Conference has accepted Helsingfors, and the Congress of Ice has accepted Leningrad as their places of meeting, only slight adjustment in time is necessary to offer maximum inducement to attend. Action by the Section of Hydrology urging such adjustment might be desirable.

Current publications

The list of current publications for the present year has been furnished by the International Association and the Baltic Conference through the agency of the American Geophysical Union, by the American Geographical Society, and by members of the Committee on Snow aided in part by student relief funds. As previously, the list is broad in order that all sources contributing to the hydrology of snow and ice may be brought within reach. As other bibliographies appear, the list may be correspondingly narrowed.

Essential publications of earlier but recent years, if not previously listed, are also included. (Unless otherwise designated, only the number of the first page of the article is given without indication of its length.)

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(3) Snow-surveying--Continued

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Programme des travaux de la conférence et liste des rapports présentés.

Conclusions (thèses et propositions) des rapports généraux: (1) Études hydrologiques complexes; (2) Écoulement (runoff); (3) Hydrologie des fleuves (rivers); (4) Hydrologie des lacs (limnologie, lakes); (5) Hydrologie des marais (swamps); (6) Hydrologie des eaux souterraines (underground waters); (7) Hydrologie des mers (seas); (8) Problèmes d'hydrologie théorique (hydromécanique et hydrophysique); (9) Hydrométrie.

Beschlüsse der Konferenz.

Selected papers (with section and current number)

Section I: Die Rolle des Grundeises im System der Wasserversorgung des gross-Leningrad, W. Altberg u. L. Mojeiko (U.d.S.S.R.); Maximal-Ausnutzung der Flüsse und der Wasserverkehr, W. Timonow (U.d.S.S.R.).

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IVeme Conférence Hydrologique des États Baltiques, Leningrad, September 1933--Continued

Selected papers (with section and current number)--Continued

Section II: Abflussprobleme, Generalbericht, Dozent D. L. Sokolowskij (U.d.S.S.R.).

Section III: Eisstudien im hydrophysikalischen Laboratorium des Hydrologischen Instituts in Leningrad, W. Altberg (U.d.S.S.R.); Winterabflüsse auf den Flüsse Swir, Prognosen und Eisbekämpfung, F. Bydin (U.d.S.S.R.); Beitrag zur Methode der Berechnung des Wasserabflusses im Winter, K. Debski (Polen); Die Arbeitsmethoden betreffend die Untersuchungen der Temperatur fliessender Gewässer, J. Matusewicz (Polen); Die Eisverhältnisse der Lettländischen Flüsse, insbesondere der Daugava, P. Stakle (Lettland); Der Zustand der Flüsse im Winter und der Einfluss wasserbautechnischer Massnahmen auf denselben, V. E. Timonow (U.d.S.S.R.).

Section V: Hydrologie der Moore, Generalbericht, Professor A. D. Dubach (U.d.S.S.R.).

Section VI: Die Unterirdischen Wasser, Generalbericht, Professor B. L. Litschkow (U.d.S.S.R.); Etude du mouvement des eaux souterraines par la méthode d'analogies électrohydrodynamiques, S. M. Proskournikov (U.d.S.S.R.); Von der flachen gefällosen anhaltenden Bewegung der Grundgewässer, B. Davison (U.d.S.S.R.); Über die Aufstellung von Regimeforschungen der unterirdischen Wasser im auf dem Gebiete der U.d.S.S.R. befindlichen Teile des Baltischen Raumes, A. A. Karpinskij (U.d.S.S.R.); Grundzüge der Klassifikation der unterirdischen Gewässer, B. Litschkow (U.d.S.S.R.); Zirkulationsverhältnisse der unterirdischen Gewässer im süd-westlichen Teil der Ostsee, N. Pogrebow u. P. Butow (U.d.S.S.R.); Laboratorium für Experimentalerforschungen des Grundwasserregimes, B. Russanow (U.d.S.S.R.); Zur Frage der Methoden zur Erforschung des Einflusses der Vegetation auf das Regime der ober- und unterirdischen Gewässer und der Zusammenhang dieser Regime, W. Rutkowsky (U.d.S.S.R.).

Section VII: Average distribution of ice along the Coast of Esthonia, K. Frisch (Esthonia); Die Schwankungen des Grundwasserstandes in Nordeutschland in den letzten zwei Jahrzehnten, W. Koehne u. W. Friedrich (Deutschland); Meteorologische und hydrologische Bedingungen der Überschwemmungen in Leningrad, S. Sowjetow (U.d.S.S.R.); Das Eis des finnischen Meerbusens nach den Angaben der Beobachtungen der Eisbrechern, V. Arnold-Alabiev (U.d.S.S.R.); Die Wirkung des Eises auf die Wasserbauten in der Newabucht, G. Garabanow und A. Richter (U.d.S.S.R.); Stationäre- und Exkursionsbeobachtungen der Eisdecke des Finnischen Meerbusens, A. Mazeino (U.d.S.S.R.); Der Eisnachrichtendienst des Baltischen Meers, W. Salomanow (U.d.S.S.R.).

Section VIII: Sur le métamorphisme de la couverture de glace, A. B. Dobrovolski (Pologne); Sur la nécessité de la fondation d'une institution internationale pour l'étude de la glace, A. B. Dobrovolski (Pologne); Die Radiationseigenschaften des Schnees und Eises, M. Kalitin (U.d.S.S.R.).

Section IX: Grundzüge einer Methode zur Erforschung der Abflussvorgänge in verkrauteten Flusstrecken, O. Faust (Polen); Die Bedeutung der Temperaturmessungen in Flüssen für die Auswertung von hydrometrischen Arbeiten, A. Winkel (Danzig).

Vème Congrès d'Hydrologie Scientifique à Lisbonne du 17 au 24 Septembre 1933, Association Internationale d'Hydrologie Scientifique [Bureau du Secrétariat Général: 26 boulevard Jourdan, Paris (XIVe)]

Bulletin N. 20:

Commission de Potamologie (rivers): Rainfall, runoff, and evaporation, Leroy K. Sherman, Robert E. Horton, and others (U.S.A.); Relation of stream-flow to annual, seasonal, or monthly rainfall, L. K. Sherman and R. E. Horton (U.S.A.); Runoff as a function of previous precipitation, William Taft Collins and Franklin Farison Snyder (U.S.A.); De l'eau qui tombe à l'eau qui coule, évaporation et deficit d'écoulement, A. Coutagne et Mme. de Martonne.

Commission de Limnologie (lakes).

Commission des Eaux Souterraines (underground waters).

Commission de Glaciologie (glaciers): Rapport sur les Variations de Longueur de Glaciers de 1928 à 1931 (1932); Chaine des Alpes et Scandinavie; Committee on Glaciers of the American Geophysical Union, Report for 1931-32, Francois E. Matthes.

Commission de Neiges (snow).

Commission pour les Applications Pratiques.

Commission pour les Méthodes Statistiques.

Bulletin N. 21 (Italy): Rapports; Previsione delle piene e della magre dei corsi d'aqua, Mario Giandotti; Le acque sotteranee nella pianura in destra di Po fra Trebbia e Panaro, Marco Visentini; Sulle rappresentazioni della distribuzione della neve, Filippo Eredia; Ricerche sull'ablazione glaciale e sulle relazioni tra variazioni glaciali e variazioni climatiche, Carlo Somigliana; Deflussi glaciali e loro influenza sul regime della Dora Baltea, Alfieri.

Appendix

Appended to this report are the following papers which have been placed on file with the Secretary of the Section of Hydrology:

Forecasting the runoff of the Columbia River Basin, J. E. Church and Clinton Twiss, Western Division, National Broadcasting Company, January 4, 1935.

Snow-conditions in the Central Sierra, the Feather River Basin, and in the Humboldt Basin, Nevada, J. E. Church and Wallace L. Kadderly, Western Division, National Broadcasting Company, February 12, 1935.

Snow-cover conditions March 1 over western United States, J. E. Church and Clinton Twiss, Western Division, National Broadcasting Company, March 11, 1935.

Utah cooperative snow-surveys and water-supply forecasts, 1935, George D. Clyde with Utah State Engineer cooperating, Utah Agricultural Experiment Station Mimeograph Sheet No. 93, April 1935.

Seasonal snow-survey and forecast of stream-flow, Nevada Cooperative Snow-Surveys, Humboldt Quadrangle, March 1, 1935, Carl Elges, Forecaster, and J. E. Church and George Hardman, Advisers.

Appreciation

The Chairman desires to mention again the generosity of the Nevada Agricultural Experiment Station which was not only the parent of western snow-surveying but has acted as patron both of the American Committee on Snow and the International Commission of Snow. Without its cooperation and financial support, many of the activities of the Committee would have been impossible. The Committee also has been greatly aided by Emily Richards, who has acted as Secretary and assumed responsibility for the Questionnaire.

Recommendation

The questions of recommending the establishing of National cooperative snow-surveys and seeking coordinated dates for the meetings in 1936 of the International Association of Scientific Hydrology, the Hydrologic Conference of the Baltic States, and the International Congress of Ice are hereby proposed for consideration by the Section of Hydrology and the American Geophysical Union. The second question may even concern other members of the Union who may wish to attend the General Assembly of the International Union of Geodesy and Geophysics and might be attracted to attend the other meetings.

Nevada Agricultural Experiment Station,
Reno, Nevada

REPORT OF THE COMMITTEE ON GLACIERS, 1934-35

François E. Matthes, Chairman

The members of the Committee on Glaciers for 1935 are as given in the report of the Committee for 1933-34 in the Transactions of the Fifteenth Annual Meeting with the addition of Kenneth N. Phillips (The Mazamas, Pacific Building, Portland, Oregon).

The year 1934 witnessed a further expansion of the program of systematic annual observations on the variations of American glaciers which was inaugurated by the Committee in 1931. Several of the collaborators in the field-work of their own initiative enlarged the scope of their activities, and a new group joined the movement in the Pacific Northwest. These are the Mountaineers, of Seattle, Washington, who began observations on the glaciers of Mount Baker, which are the largest in the continental United States next to those on Mount Rainier. Under the leadership of H. V. Strandberg a base-line was laid out by the Mountaineers for measurement of the recession of the Easton Glacier, on the south side of the peak.

Park Naturalist C. Frank Brockman added a sixth to the list of glaciers on Mount Rainier on which he is making annual measurements. This is the Stevens Glacier, on the southeast side of the peak.

Richard M. Leonard, of the Glacier Study Committee of the Sierra Club, made a preliminary visit to the seven small glaciers that cling to the northeast flanks of Twin Peaks, Matterborn Peak, and Sawtooth Ridge, and that constitute the northernmost group of glaciers in the Sierra Nevada. He has given the first detailed descriptions of these hitherto little-known ice-bodies.

The Committee on Glaciers wishes to avail itself of this opportunity to express its appreciation of this enthusiastic and effective cooperation, and to thank all those who so generously are giving of their time and energy to secure the desired data on the variations of American glaciers.

No reports were received in 1934 on any measurements on Alaskan glaciers, outside of those in Mount McKinley National Park, which are mentioned on another page. However, this does not imply that the year went by without any substantial contributions being made to our knowledge of the glaciers of Alaska. A noteworthy contribution is embodied in a forthcoming bulletin of the United States Geological Survey on The Southern Alaska Range, by Stephen R. Capps, which is accompanied by two topographic maps by R. H. Sargent, Gerald Fitzgerald, and K. W. Trimble.

Although in the reconnaissance-methods employed ice-bodies less than one mile in length were not as a rule considered of sufficient importance to be shown, nevertheless there are indicated on these two maps (not published) nearly 200 glaciers, practically all of which were previously undescribed and unnamed. Of these glaciers 30 are four miles or more in length. Triumvirate Glacier, the largest ice-mass in the region, is fully 28 miles long and has an area of about 170 square miles. Adjoining it to the south is an unnamed ice-stream 25 miles long and 75 square miles in area, and at the head of the McArthur River is another glacier which, though only partly surveyed, is known to be at least 24 miles long. The largest glaciers all lie in deep canyons in the eastern or Cook Inlet flank of the mountains, which receives much heavier precipitation than the western inland slope.

Another significant contribution was made by the aerial Patrol Squadron attached to the U.S.S. Wright which visited southern Alaskan waters in the summer of 1934. On their flights along the coast the fliers of this Squadron took many excellent photographs of the fronts and other features of 19 major glaciers--namely, of the Bering, Godwin, Pederson, Bear, Malaspina, Mendenhall, Norris, Twin (both branches), Halgate, Columbia, Aialik, Taku, Wright, Crillon, Northwestern, Skee, and La Perouse glaciers, and one unidentified glacier. The Committee on Glaciers is indebted to these Naval officers for a set of 82 of these photographs, which were presented to it for its files and which will have great value in future comparative studies of the oscillations of the ice-fronts.

A contribution of a somewhat different sort was made by H. Bradford Washburn and Richard P. Goldthwait, of the Harvard-Dartmouth Expedition to Mount Crillon, on the Fairweather Range, in southeastern Alaska. With the aid of a new device, visible at night as well as in the day, which was furnished by Hamilton Rice of Harvard University, hourly observations were made on the motion of the South Crillon Glacier, which was found to move not steadily but by successive surges, at definite periods during every 24 hours. By the geophysical blasting method the depth of the glacier was determined to be about 1100 feet; and a fine series of aerial photographs was obtained on a flight from Crillon Lake up along the coast to Yakutat Bay, thence over Nunatak Fiord, Disenchantment Bay, and the Hubbard Glacier, to the Malaspina and Libbey glaciers, and back to Crillon Lake, with a detour encircling the summit of Mount Crillon. A preliminary popular account of the expedition was published in the National Geographic Magazine for March, 1935.

The Committee submits below a report on the variations of American glaciers for the year 1934--more specifically, for the 12 months from the autumn of 1933 to the autumn of 1934.

Glaciers of Mount Rainier

Park Naturalist C. Frank Brockman, in a report illustrated with many excellent photographs, gives the following figures for the five glaciers measured by him:

Nisqually Glacier, on the south side of Mount Rainier, in 1934 set a new record with a recession of 155 feet. This is a truly startling figure as compared with 44 feet in 1933 and 50 feet in 1932. It far exceeds the greatest recession measured in any previous year, which was 118 feet in 1930. The average recession for the past 15 years has been 67 feet per year. The lowest recession was 43 feet in 1927.

The total shortening suffered by the Nisqually Glacier since 1918, when annual measurements were begun by the National Park Service, now amounts to 1164 feet. (The total of 928 feet, up to 1933, which was given in last year's report, is in error and should have been 1009 feet.) As the position of the glacier's terminus in 1857 is known with a fair degree of accuracy from the descriptions of Lieutenant (later General) A. V. Kautz, who in that year made the first attempt to climb to the summit of Mount Rainier, the total recession is known since that early date also. From 1857 to 1918 it amounted to 2210 feet; hence the grand total now is 3374 feet, or a little short of two-thirds of a mile.

The abnormally great recession of the Nisqually in 1934, according to Mr. Brockman, was due to excessive ablation during an "early, open, and very warm summer" following upon a winter marked by very light snowfall. The effects of these climatic influences are reflected also in the records of the other glaciers on Mount Rainier, every one of which receded a greater distance in 1934 than in any previous year.

Paradise Glacier, on the southeast side of Mount Rainier, was measured at three points on its one-half mile broad front. At point A, on the west side, which was covered with snow in 1933, there was a recession of 7 feet since 1932. At point B the recession in 1934 was 34 feet as compared with 5 feet in 1933. At point C the recession in 1934 was 24 feet, as compared with 7 feet in 1933.

The Paradise Glacier, as Mr. Brockman points out, is really but the southwesterly lobe of the Stevens Glacier, and is now so greatly reduced in volume as to be almost stagnant. The main current in the ice-mass flows southeastward to the active lobe which feeds Stevens Creek. A reference point was established by Mr. Brockman in 1934 near the front of this active lobe of the Stevens Glacier, and measurements will hereafter be made from that new reference-point.

The record of the Stevens Glacier is likely to prove of peculiar interest because that Glacier, unlike the others that are being measured annually, is not alimented by the summit névés, either by névé cascades or avalanches, but originates independently on the east flank of the ridge below Anvil Rock, at altitudes ranging from 8000 to 9000 feet--that is, 5000 to 6000 feet below the summit of the peak. It belongs to the class of secondary glaciers that occupy sloping table-lands situated near the base of Mount Rainier and between the steep-walled canyons of the great primary glaciers.

Emmons Glacier, the longest and largest ice-stream in the continental United States, receded 132 feet in 1934, as compared with 48 feet in 1933, 2.5 feet in 1932, and 142 feet in 1931. These figures, it should be pointed out, are probably not all representative of the actual variations in the recession of the terminus that have occurred from year to year, for the earlier measurements were made in each case to the point of exit of the stream, whose position is inconstant. The figure for 1934 is probably more nearly representative than the others. The great recession which it indicates gains significance when it is considered that the Emmons Glacier is situated on the northeast side of the peak and is alimented by névé cascades from the summit that are over a mile in width.

Carbon Glacier, which heads in a shady cirque on the north side of Mount Rainier, and is further shaded in its lower course by the walls of a narrow canyon, receded, as might be expected, far less than any of the other primary glaciers on the peak that were measured. Its terminus in 1934 receded 29 feet as compared with 12 feet in 1933. The Carbon Glacier continues to hold the record among the glaciers of the continental United States for the low altitude of its terminus--somewhat less than 3400 feet above sea-level.

Glaciers of Mount Hood

Kenneth N. Phillips, Chairman of the Research Committee of the Mazamas, of Portland, Oregon, reports that the glaciers on Mount Hood receded much farther in 1934 than in any previous year since 1925, when regular measurements were begun. At the end of the summer all the glaciers were largely divested of snow, and their crevassed ice was exposed to a greater extent than had ever been observed.

Eliot Glacier in 1934 showed a recession of 40 feet, as against an advance of 25 feet in 1933.

Coe Glacier had receded 24 feet from the position occupied by its front in 1932. No measurements could be made on this Glacier in 1933, but as it doubtless, like the Eliot, made a substantial advance in that year, it may be presumed that its actual recession in 1934 was considerably more than 24 feet.

Ladd Glacier, unfortunately, could not be reached in 1934, owing to stormy weather.

The unusually great recession of the Eliot and Coe glaciers is readily accounted for by the exceptional warmth and the deficiency in precipitation during the 12-month period from October 1, 1933, to September 30, 1934. As is evident from a tabulated summary of Weather Bureau records for Oregon, which was transmitted by Mr. Phillips, the temperature-excess was general and prolonged, but most marked during the winter and spring months. December, 1933, and January, February, March, and April, 1934 were all of them record-breakers for warmth. October, 1933, was the

warmest October since 1907; May, 1934, was the warmest May recorded except one; and August, 1934, was the warmest August since 1915. Precipitation was below normal in all months except three--October and December, 1933, and June, 1934. Precipitation in November was the lowest recorded for that month, except in two other years. December turned out very wet, but the heavy snowfall on the mountains was offset by the unusually high temperatures.

Glaciers of Mount Shasta

Oliver Kehrlein, Chairman of the Committee on Glacier Studies of the Sierra Club, revisited several of the glaciers on Mount Shasta early in September, 1934, and in his report furnishes further data and photographs of these little-known ice-bodies.

Wintun Glacier, on the east side of Mount Shasta (observations on which had to be suspended in 1933, owing to inclement weather), was given particular attention, and a base-line was established at its south lobe, which is the longest. Fortunately the position of the terminus of that lobe in 1927 is known with a fair degree of accuracy, and as a result the distance which that lobe has receded since that date could be determined as being approximately three-quarters of a mile. The terminus is now close to the 10,000-foot contour-line, whereas it lay at an altitude of 8300 feet in 1927.

Wintun Glacier now has four distinct lobes occupying broad, shallow channels in the mountain's side separated from each other by low rock ridges. Photographs taken in 1895 and 1920, however, show that in those years the three northerly lobes coalesced over the ridges so as to form a single continuous ice-mass one-half mile broad. It is thus evident that the Wintun Glacier has suffered a considerable reduction in extent and in volume during the last 14 years.

Mr. Kehrlein calls attention, further, to certain features which, though still somewhat puzzling, very probably are to be interpreted as indicating another much greater reduction in the extent of the Wintun Glacier which must have taken place in relatively recent times. These features consist of residual masses of ice cropping out here and there from beneath the great embankments of loose volcanic debris that flank the now empty glacier trough for more than a mile below the terminus of the Wintun Glacier. The most reasonable interpretation, for the present, seems to be that while the glacier lay in the trough the volcanic debris accumulated along its sides, being derived in part from the crumbling canyon walls and in part from the heavily loaded glacier itself. As the glacier's surface was finally lowered by excessive melting the loose debris slumped down upon its margins, burying considerable masses of ice and preserving them. At present the gradual retreat of the debris-slopes, by slumping and rain wash, brings these buried ice-masses again to light in spots. Just how far back in time this chapter in the glacier's history goes is still a matter of conjecture; but the exceeding steepness and the raw aspect of the flanking debris-slopes in any event strongly suggests that it is likely to be a matter of decades rather than centuries.

Hotlum Glacier, the largest glacier on Mount Shasta, situated on its northeast side, appears to have been reduced in size and split up into lobes during the last 14 years in much the same way as the Wintun Glacier. A photograph taken 1920 shows that it then was a single continuous ice-mass covering the slope of the mountain over a breadth of about 1.5 miles. Today it is composed of two lobes separated by a rocky ridge, and the southeast lobe has shrunk to a narrow tongue that reaches, by estimation, no lower than 12,500 feet. The northwest lobe still maintains a breadth of about one mile and has a length, from cirque wall to terminus, of somewhat more than one mile. Comparison with a photograph taken in 1920 shows that its broad, strongly lobate front has receded considerably and that the lower portion of the mass has melted down appreciably since that date.

If all the other glaciers on Mount Shasta have been reduced proportionately as much as Hotlum and Wintun since 1920, the ice-mantle of Mount Shasta as a whole may have suffered greater losses in proportion to its mass than the ice-mantle of Mount Rainier has suffered in the same interval.

Mud Creek Glacier receded about 40 feet in 1934. Its terminus actually overhangs the caving wall of volcanic ash at the head of Mud Creek Gorge, and it is therefore evident that in its case recession is due not merely to melting but also in large measure to undermining of the terminus by the headward erosion of the streamlet in the gorge.

Konwakiton Glacier, which lies at a much higher level than Mud Creek Glacier, had changed but little since last year, so far as could be determined from a comparison of photographs.

Glaciers of Sierra Nevada

From the beautifully illustrated report of Park Naturalist C. A. Harwell it is evident that the glaciers in and adjacent to Yosemite National Park continued to recede in 1934, some of them more rapidly than in preceding years, others less rapidly. The recession of their fronts, however, is hardly expressive of the losses sustained by ablation at their surfaces, which again this year were stripped of snow up to high levels. Deficiency of snowfall during the winter of 1933-34 chiefly accounts for this condition.

East Lyell Glacier showed a recession at the central part of its broad front of 21 feet, as compared with a recession of 18 feet in 1933, and of 2 feet in 1932.

Comparison with a photograph taken by I. C. Russell in 1883 shows that the East Lyell Glacier has receded a net total of about 300 feet and has lost appreciably in thickness since that early date. Another photograph, taken by Lloyd Hennig, in the early 1890's, likewise reveals that in those years the glacier had considerably greater volume.

West Lyell Glacier in 1934 receded 14 feet as compared with 7 feet in 1933 and with an advance of 6 feet in 1932. A photograph taken by Lloyd Hennig in the early 1890's shows that at that time the upper portion of the Glacier was so much thicker than it now is that one could reach the rocky crest of Mount Lyell by a simple climb up a continuous snow-slope.

Maclure Glacier in 1934 had receded 15 feet as compared with 22 feet in 1933.

Dana Glacier, as in previous years, was measured at four points on its broad and irregular front. At station 4, which is not far from the center, the ice had receded 46 feet, as compared with 30 feet in 1933, and with an advance of 31 feet in 1932.

From a photograph taken by I. C. Russell in 1883 it would appear that the Dana Glacier has receded a net total of about 100 feet since that year. This may seem a trifling distance as compared with that of three-quarters of a mile through which the Wintun Glacier on Mount Shasta has receded within the last 14 years; however, it is evident from Professor Russell's photograph that the Dana Glacier has lost considerably in thickness and volume also. Assistant Park Naturalist M. E. Beatty estimates that the loss in volume may amount to fully one-third.

Conness Glacier on October 10, 1934, was found covered with 2 feet of fresh snow, and no accurate measurement therefore could be made to its, at best, indefinite frontal margin. The estimated recession is about 25 feet.

North Palisade Glacier, the largest glacier in the southern part of the Sierra Nevada, was not measured in 1934, but from photographs received from Oliver Kehrlein, Chairman of the Committee on Glacier Studies of the Sierra Club, it is apparent that this glacier in 1934 suffered further reduction in volume, its surface having again been lowered by strong ablation.

Glaciers in Glacier National Park

The following data were received from Park Naturalist Geo. C. Ruhle:

Blackfoot Glacier (west lobe) at the end of the summer of 1934 had receded 10 feet from the position it occupied in 1933.

Grinnell Glacier showed a recession of 54 feet as compared with none in 1933.

Agassiz Glacier, which owing to stormy weather could not be reached in 1933, was found to have receded 75 feet during the period 1932-34.

Glaciers in Rocky Mountain National Park

John C. Preston, Assistant Superintendent, reports that the recession of the glaciers in Rocky Mountain National Park was greatly accelerated in 1934 as a result of warm weather and scanty precipitation.

Tyndall Glacier in 1934 receded 42 feet, as compared with 33 feet in 1933.

Andrews Glacier in 1934 receded fully 80 feet, as compared with 9 feet in 1933.

Glaciers in Mount McKinley National Park

The report received from Harry J. Liek, Superintendent of Mount McKinley National Park, shows that Sunset Glacier had neither advanced nor retreated since 1933.

Toklat Glacier could not be definitely measured owing to fresh snow, but appeared to have changed but little since 1933.

U. S. Geological Survey,
Washington, D. C.

REPORT OF THE COMMITTEE ON EVAPORATION, 1934-35

George F. McEwen, Chairman

The membership of this Committee remains the same as given in the Transactions of the Fifteenth Annual Meeting.

The following manuscripts were submitted and are published in this volume: N. W. Cummings, The use of the Burt phototube in an integrating pyrheliometer; S. T. Harding, Evaporation from large water-surfaces based on records in California and Nevada.

An extensive list of requests for information pertaining to evaporation was presented in the report, April 1934, and should continue to receive careful consideration.

An additional project of great practical importance is to work over existing evaporation-records for the purpose of presenting a summary of the rate of evaporation according to appropriate geographical regions. Such an undertaking would involve various supplementary questions raised in the last report and in the tentative outline prepared to serve as a guide for the work of the Committee.

Scripps Institution of Oceanography, University of California,
La Jolla, California

REPORT OF THE COMMITTEE ON ABSORPTION AND TRANSPIRATION, 1934-35

Charles H. Lee, Chairman

The members of the Permanent Research Committee on Absorption and Transpiration are as given in the Transactions of the Fifteenth Annual Meeting.

The climatic extremes of the past few years in various parts of the United States have aroused widespread public interest in ground-water conservation and the control of floods and soil-erosion, and as a result hydrologic research has been greatly stimulated. Directly or indirectly, much of this research involves the subjects of absorption and transpiration. Contributions to ground-water from precipitation and stream-flow, for example, depend upon absorptive capacity of the soil and transpiration from vegetation, and all ground-water research produces more or less data regarding these subjects. Similarly the study of flood-flow and soil-erosion, although directly concerned with immediate runoff from precipitation, yet produces data regarding absorption because of the complementary nature of runoff and absorption. Consequently there is much current hydrologic research which is within the field of interest of this Committee.

The main portion of the Committee's report is a brief review of the current work being done on the subject of absorption and transpiration throughout the United States to the extent that it has come to the attention of Committee members.

In addition to the review of current research-activities the Committee has continued its work upon the list of definitions of terms pertaining to absorption and transpiration. The tentative definitions presented with last year's report have been extensively revised as a result of comments submitted both by Committee members and by non-members of recognized authority. The list of terms with definitions as finally revised is presented as part of this report, and accompanies it as Appendix A. It is hoped that these definitions will help to clarify thinking in this field of hydrology, and facilitate interchange of ideas with other fields of research.

Research in absorption of rainfall and transpiration by the California Forest and Range Experiment Station, United States Forest Service, Berkeley, California

Research-studies are being continued in factors affecting absorption of rainfall and transpiration in the program of forest influences of the California Forest and Range Experiment Station. Work is being carried on at the following locations:

(1) San Dimas Experimental Forest, area 17,000 acres--A major watershed study in the chaparral type of southern California, described in the report for 1933-34. The complete program involves an expenditure of over $500,000.
(2) North Fork and Bass Lake, Sierra National Forest--Studies employing plots 1/40-acre in area for observing runoff and erosion, and lysimeters for measuring percolation.
(3) Berkeley--Plot and lysimeter studies similar to those in (2).

A search is now in progress for suitable small watersheds in the southern Sierra Nevada Mountains, to be employed in a study of the influence of various cover-types upon the beneficial yield of water from mountain watersheds. Work will be initiated in the true fir and foothill brush-types during the coming summer. In each of these types three or more contiguous watersheds of 50 to 500 acres each will be subjected to intensive study.

In connection with the San Dimas Experimental Forest, various-sized lysimeters are now being installed to determine the loss of water occasioned by the presence of chaparral species and forest trees. They include 48 small weighing types, unit weight 350 pounds, sensitive to 7 grams; 30 large weighing types, unit weight 1800 pounds, sensitive to 8 ounces; 18 large concrete types, 10-1/2 by 21 feet by 6 feet deep; and one large lysimeter, in situ, which will isolate within concrete walls a block of chaparral-covered hillside, approximately 24 by 36 feet in surface dimensions and 20 feet deep.

Research in absorption of rainfall and stream-flow by the Appalachian Forest Experiment Station, United States Forest Service, Asheville, North Carolina

Researches as described in the report for 1933-34 have been continued in the comparative efficiency of different types of vegetative cover in maintaining favorable absorption-conditions for watershed-protection. New installations include the establishment of 26 small watershed-units ranging from 10 acres to 2000 acres and representing different types of land use and vegetative cover. Each of these watersheds has been equipped with a weir-installation and silting basin. A system of intensity and standard rain-gages has been established for each watershed.

Two major watershed-studies have been developed. The Coweeta Experimental Forest in western North Carolina has been developed with the purpose in mind of studying vegetation and the management of watersheds in a region of rough topography with an 80-inch rainfall. This area of 4500 acres constitutes a complete watershed that is made up of four smaller watersheds of approximately equal size, and each of these smaller watersheds is in turn made up of a number of smaller units, each supporting a continuous stream. The development of this area includes meteorological stations and wells for the study of ground-water and ground-water movements.

A second major watershed-study is being developed within the Copper Basin of Tennessee. The Basin, once covered by a heavy hardwood forest, lies in a 60-inch rainfall belt. It has been greatly modified by fumes incident to copper and iron mining. Areas being studied represent forest-cover, broomsedge-cover, and complete denudation by smelter fumes. Meteorological stations are now in operation. The eroded portion of the Copper Basin has been depleted to a stage beyond possible use for agriculture, but may possibly be restored to more favorable watershed-conditions through forestry.

Research on transpiration by the Southern Forest Experiment Station, United States Forest Service, New Orleans, Louisiana

Studies are being initiated at the Harrison Experimental Forest of this station on the water requirements of the four principal southern pine species, namely: Longleaf (Pinus palustris), slash (Pinus caribaea); loblolly pine (Pinus taeda); and shortleaf pine (Pinus echinata). This study includes measurements of water lost through transpiration and evaporation from the pines under different environmental conditions.

In connection with erosion and stream-flow in the Holly Springs, Mississippi, branch of this station, records are being kept on the surface-runoff in the silt-loam uplands.

Intermountain Forest and Range Experiment Station,
United States Forest Service, Ogden, Utah

Studies are being made of the effect of depletion of vegetation and denudation of plant-litter by over-grazing and fire upon absorption and runoff in mountain canyons of northern Utah. Preliminary data have been published in Miscellaneous Publication No. 196, United States Department of Agriculture, entitled "Floods and accelerated erosion in northern Utah" by Reed W. Bailey, C. L. Forsling, and R. J. Becraft, 1934.

Division of Irrigation, Bureau of Agricultural Engineering,
United States Department of Agriculture

The research-work of this agency on projects listed in the last annual report of the Committee has continued during the past year.

A comprehensive report on storage of water underground by spreading, covering all of Southern California, has been completed in manuscript form and will be published in the near future.

Bulletin No. 46, Division of Water Resources, State of California, 1934, Chapter VI, by Harry F. Blaney, Irrigation Engineer, presents the results of one-year's study of the absorption of rainfall in valley areas of Ventura County, California, based on soil-moisture and rainfall records at 16 stations.

The contribution of rain falling on the valley floor to the ground-water supply for a five-year period is estimated. The method used is described. The report includes a map showing location of the rainfall penetration stations and the 13 basins considered.

Factors in rainfall disposal such as initial soil-moisture deficiency, runoff, evaporation, and transpiration, were determined and used in computing the amount of rainfall penetrating below the root-zone. Evaporation-loss for each month was computed from daily rainfall-records on the basis of 1/2-inch loss after each storm. The transpiration-loss for all active-growing agricultural crops was taken as 1 inch per month for the summer period. For native vegetation, evaporation- and transpiration-losses were combined at the rate of 2 inches per month for grass and weeds and 2.4 inches for brush, provided sufficient rain fell to meet their demands. The effect of irrigation during the rainy season was considered.

The amount of rainfall penetrating below the root-zone for a typical station for the year 1931-32 is estimated for different crops, as follows: Citrus, clean cultivated, usual practice, 5.9 inches; deciduous, clean cultivated, 2.5 inches; beans, non-irrigated, 6.4 inches; bare land, 9.4 inches; grass and weeds, 1.2 inches; and brush, zero inch. Total seasonal rainfall at this station was 18.68 inches. (Reprints of this report are available and can be obtained from W. W. McLaughlin, Chief of the Division of Irrigation, United States Department of Agriculture, P.O. Box 180, Berkeley, California.)

Division of Water Resources, Department of Public Works,
State of California, Sacramento, California

Bulletin No. 45--South Coastal Basin Investigation, Ground-Water Storage Capacity of Valley Fill, 1934. This report presents the results of the most complete study of the water-holding properties of various types of sedimentary materials which has come to the attention of the Committee. Investigations extended over the entire South Coastal Basin of California comprising approximately 2,500,000 acres, nearly half of which is valley land overlying productive ground-water basins supporting a population of about 2,800,000 people. Geological studies were made of 35 ground-water basins to determine the nature of basin-boundaries, the physical character of the basins, and their relation to the occurrence and movement of ground-water. Physical studies were made to determine the storage capacity of each basin in order to convert into volumetric storage-changes the rise and fall of the water-table resulting from absorption and draft. Several thousand samples of typical gravels, sands, and clays were obtained from surface exposures, pits, and wells. Porosity and mechanical analysis determinations were made of 350 samples, and moisture-retention of about 150. Several comprehensive studies of general technical interest were made involving relations of porosity, mechanical analyses, specific yield, and specific retention. The results of these studies have direct application to determination of the amount of permanent absorption by the water-table method.

Coarse alluvial material consisting of sand, gravel, and boulders, was found to have the least void with a porosity of about 17 per cent and specific yield of 14 per cent. Coarse sand had the highest specific yield with a porosity of 40 per cent and specific yield of 32.5 per

cent. Fine sand with silt and clay was found to have a maximum void exceeding 44 per cent, but a minimum specific yield, the latter being less than 10 per cent.

Soil Erosion Service, United States Department of Agriculture, Washington, D. C.

The Soil Erosion Service itself has thus far made no investigations or studies on absorption and transpiration, but such work is very definitely included in plans outlined for 1935 and 1936. This research work will be directed by W. C. Lowdermilk, Vice-Director, who has been prominent in similar investigations for years.

Through cooperation of the United States Geological Survey, gaging stations to measure run-off and stream-flow have been established on many of the Soil Erosion Service watershed-projects. This phase of the work will be continued and expanded. Lysimeter-studies will be made and other hydrological data compiled under the supervision of D. B. Krimgold, who has been placed in active charge of the work by Dr. Lowdermilk.

Ground-Water Division, United States Geological Survey, Washington, D. C.

The results of several years rainfall absorption-observations at 10-foot square plots near Lodi, California, are being studied, and it is planned to publish the data in the near future. The investigations have been made under the direction of A. M. Piper, Geologist, Lodi, California, in connection with a general study of ground-water conditions on the alluvial fan of Mokelumne River.

A nation-wide program of water-level measurements in wells has been inaugurated as the result of the extensive drought conditions of the past few years. The Mississippi Valley Committee of the Public Works Administration and the Soil Erosion Service are both interested. Periodic measurements are now being made on more than 1300 wells in areas where no heavy artificial withdrawals of ground-water are being made. Many of these wells are located in areas of ground-water intake that are not influenced by heavy pumping. These wells are located principally in the states of Connecticut, Kansas, Maryland, Michigan, Missouri, North Carolina, Pennsylvania, Nebraska, Virginia, Washington, and Wisconsin. As the records of fluctuations in these wells accumulate, they will become more and more valuable in making studies of rainfall-penetration and withdrawals by transpiration. At present the efforts of the Ground-Water Division are directed toward the establishment of observation-wells to obtain reliable records, but it is contemplated that as soon as sufficient records are obtained, valuable interpretations can be made as to both absorption and transpiration of ground-water.

Water Conservation Committee, Irrigation Division, American Society of Civil Engineers, 925 Central Building, Los Angeles, California

At the conference held by this Committee at Los Angeles, California, on March 13 and 14, 1935, there were several papers submitted giving results of measurements of runoff from artificial rain upon small test-plots. Tests have been made at several hundred points upon typical slopes and soils in steep mountain drainage-areas from which destructive flood-runoff occurs. The primary purpose is to determine the rate of maximum runoff from maximum rainfall-intensity, but the data also serve to establish the maximum rate of absorption from rainfall. These tests have been conducted by the Los Angeles County Flood Control District, 205 South Broadway, Los Angeles, California; Bureau of Engineering, Storm Drain Department, City Hall, Los Angeles, California; and the Bureau of Water Works and Supply, Department of Water and Power, City of Los Angeles, 207 South Broadway, Los Angeles, California. The Water Conservation Committee plans to publish these papers in the near future.

Bureau of Water Works and Supply, Department of Water and Power, City of Los Angeles, 207 South Broadway, Los Angeles, California

A unique method for artificial stimulation of absorption from precipitation upon a dry soil was developed by the Department during the construction of a large earth-fill dam in Bouquet Canyon. It was desired to pre-moisten the earth-material used in construction of the dam, and for this purpose sprinklers were installed at the borrow pit to moisten the material in the bank in advance of steam-shovel excavation. Experiencing delay in penetration of moisture into the ground because of air-binding beneath a shallow layer of saturated material at the top of the soil-column, vacuum pumps of the injector-type were installed to remove the entrapped air from the soil. This procedure was found to be very effective in speeding up the advance of moisture

into the dry soil, the apparatus acting both to remove air from the soil and to create a pressure differential. The apparatus was inexpensive and simple to install. The method was developed by R. R. Proctor, Field Engineer, under the direction of H. A. Van Norman, Chief Engineer and General Manager. Since construction of the dam experiments have been made with the apparatus by N. M. Imbertson, Assistant Field Engineer, which indicate that it has a wide practical application in the conditioning of agricultural soils. Absorption can be increased from rainfall or irrigation upon tight soils, warm air, or soluble fertilizers can be drawn down into the root-zone, etc., etc.

Future work

The Committee has thus far been unable to make much progress on the proposed statement of the present status of the subject of transpiration, an outline for which accompanied the 1933 report. It is hoped that some progress can be made on this project during the coming year. In the near future it is planned to invite suggestions for other special activities.

58 Sutter Street,
San Francisco, California

APPENDIX A--LIST OF TERMS WITH DEFINITIONS

Introduction

The purpose of these definitions is to formulate in concise terms the basic ideas pertaining to the subjects of absorption and transpiration. Certain descriptive matter as well as many of the definitions are well known to soil physicists and geologists, and may seem superfluous. It should be pointed out, however, that the definitions are intended primarily for the use of hydrologists, many of whom approach the subject from other backgrounds such as engineering, meteorology, forestry, or botany. It is hoped that the definitions will serve to facilitate the exchange of ideas among hydrologists and encourage utilization of the results of research in other related fields, and in foreign countries. It is believed that recent research-work in the physics and chemistry of liquid surfaces and of molecular attraction is an especially fruitful field for study in connection with the movement of soil moisture in unsaturated materials.

Definitions standardized by previous usage have been followed as far as possible. The processes involved in absorption have received so little analytical study, however, that it seemed desirable to make more specific the meaning of certain loosely-defined terms in general use, and to propose new terms for certain processes or conditions which frequently are not clearly recognized among hydrologists. The proposal of new terms has been undertaken only when it was felt by several members of the Committee that adequate terms were lacking. Where possible, definitions have been purposely stated so as to make a distinction between saturated and unsaturated materials.

The definitions incorporate all suggestions which have been offered by members of the Committee during a period of nearly three years, but the list does not include all terms which have been suggested. In addition to receiving the contributions of members, the published works of leading hydrologists and soil physicists have been freely consulted, including those of Meinzer, Meyer, Horton, Lebedeff, Terzaghi, Hogentogler, Israelsen, and Veihmeyer. The results of research work in the physics and chemistry of surfaces have also been reviewed, reference having been made especially to the works of Adam (The physics and chemistry of surfaces, N. K. Adam, Oxford University Press, 1930) and Rideal (An introduction to surface-chemistry, E. K. Rideal, Cambridge Press, 1926).

During the current year detailed comments upon the tentative statement of definitions accompanying the 1934 Report of the Committee have been received from O. E. Meinzer, F. J. Veihmeyer, N. E. Edlefsen, and A. M. Piper. These comments have been very helpful and have resulted in considerable revision of definitions and some addition and elimination.

For convenient reference, the definitions have been arranged under certain headings. Those classified as "general" pertain principally to the solid material which forms the container or supporting framework for subsurface water. This heading also includes the definition for "precipitation," which is the ultimate source of all subsurface water. These definitions are all well known and need no comment.

Under the heading "subsurface water" are included definitions of the various zones and classes of subsurface water. The terms "pellicular water" and "mobile water" are new. Their intro-

duction is occasioned by the fact that capillarity is, strictly speaking, a special case of the more general phenomena of surface-pressure of liquid surfaces. The phenomenon of capillarity, although produced by the negative pressure of concave liquid surfaces, pertains specifically to the rise of a liquid in small tubes immersed in the liquid. It is illustrated in nature by the capillary fringe above a water-table. On the other hand, water occupying films in the zone of aeration above the capillary fringe is beyond the influence of capillarity, being controlled partly by the forces of surface-pressure in films, partly by gravity, and partly by the molecular forces of adhesion. It is believed that the analysis of the behavior of soil water above the capillary fringe can be made more clearly if divorced from association with the special phenomenon of capillarity. It is with this consideration that the new terms "pellicular water," referring to that held by the forces of molecular adhesion, and "mobile water," referring to that controlled by the forces film-pressure and gravity, have been introduced. The term "fringe-water" has been applied to mobile water within the capillary fringe.

The subject heading "movement of subsurface water" includes the three terms "film-flow," "percolation," and "cavern-flow," which are descriptive of flow-types; the terms "free-surface energy," "film-pressure," and "potential," descriptive of forces which actuate film-flow; and the terms "permeability" and "impermeability," which characterize solid materials with reference to the movement of subsurface water. "Film-flow" is a new term occasioned by the elimination of the term "capillary." Its purpose is to differentiate the flow through films in unsaturated material from that in saturated material below the water-table. For the latter the term "percolation" is reserved. Interstitial sizes differ widely in natural materials, and a portion of the voids may be saturated in the capillary fringe. Movement within the capillary fringe is considered to be film-flow, however, because of the presence of a certain amount of air. The function of film-pressure in the movement of suspended water has not been as generally recognized by hydrologists and engineers as is warranted by its importance. This is especially true with respect to the entry-head of surface water discharging into unsaturated material and the movement of suspended water above the capillary fringe.

"Soil-water" terms were included in the definitions because of their usefulness in the study of infiltration and transpiration. Among these, "specific retention" and its complement "specific yield" have been developed to their present degree of accuracy in connection with hydrologic work. The former, if carefully measured, essentially represents the sum of pellicular and hygroscopic water.

There are a number of soil-water terms common in agricultural and highway subgrade practice. Some of the former have had wide use in practical agricultural field-work, and a majority of the Committee considered their inclusion desirable. It is not to be understood, however, that the list of such terms is complete. The list includes "moisture-equivalent," "field-capacity," etc. "Moisture-equivalent" is easily measured, and in many soils is representative of the maximum moisture of which a portion is available to plants. It includes the more slowly-moving portion of mobile water and the available portion of pellicular water. "Field-capacity" closely corresponds with "moisture-equivalent" in all but the sandier soils, in which it more accurately represents the maximum moisture of which a portion is available to plants, than does moisture-equivalent. Such terms as "permanent wilting-percentage," "ultimate wilting-point," "wilting-range," "available water," "readily available water," and "initial moisture-deficiency," which are in practical use, were not included because of disagreement as to definition and general usefulness. For definitions, reference can be made to California Agricultural Experiment Station Bulletin 479, California Agricultural Extension Service Circular 50 (p.71, and Transactions, American Geophysical Union, Fifteenth Annual Meeting (Part II, p. 437).

Under the heading "absorption" is included its definition and that of the various processes by which absorption takes place. The terms "wetting" and "spreading" are defined in accordance with their accepted technical meaning and are included for the purpose of presenting all the essential steps by which water enters the ground. "Infiltration" is a term frequently used in a sense more or less synonymous with absorption, but has been limited to liquid water. The limited aspect of the term has been retained in the definition, and it has been further limited to water entering the zone of aeration. Loss of water from streams into unsaturated material is included in infiltration. "Seepage" is limited to flow into or from saturated material following the definition given by Meinzer. The terms "rainfall-penetration" and "water-spreading" are in common use and their definitions generally accepted.

The more commonly used terms relating to "runoff" are included because of the close relation of infiltration and runoff. The definitions are all generally accepted.

General

Atmosphere--The outer part of the Earth surrounding the lithosphere and hydrosphere, and consisting predominantly of air.

Hydrosphere--The liquid and solid water resting upon and invading the outermost zone of the lithosphere.

Lithosphere--That part of the Earth which is composed predominantly of rocks, including the products of rock-disintegration and other incoherent solid materials, together with everything within the rocky crust.

Earth--The softer materials of the lithosphere as distinguished from firm rock. Its basic constituents are the products of rock-disintegration, glaciation, and erosion, consisting of boulders, cobbles, pebbles, gravel, sand, silt, and clay, the latter in both particle and colloidal form. It may also be of organic, diatomaceous, or volcanic origin.

Soil--The top layer of earth penetrated by roots and containing more or less organic matter. It includes the surface soil (horizon A), the subsoil (horizon B), and the upper portion of the substratum to the extent penetrated by plant and tree roots (horizon C).

Interstice--A pore-space or void in rock or earth not occupied by solid matter. Interstices have been termed continuous if connected with one another, discontinuous if unconnected. Continuous interstices occur as (1) openings between particles or grains in earth or rock, (2) fractures in rock, and (3) as large tubular or cavernous openings in soluble rocks and in lava-flows. Discontinuous interstices occur as small cavities in lava and other effusive igneous rock of a vesicular or pumaceous texture. Discontinuous pore-space, although it may aggregate a considerable part of the total volume of the rock, does not impart permeability. Interstices have also been termed primary if existing in the sediment from which the rock was formed by consolidation, or secondary if formed after the consolidation of the rock.

Capillary interstice--One small enough for water to be held by capillarity at an appreciable height in a capillary fringe above a water-table or hydrostatic pressure-level, and large enough to preclude molecular attraction of its walls from spanning the entire space. Such water is partly pellicular and partly mobile. The movement of water through saturated capillary interstices conforms to the laws of stream-line flow, whether acting under hydrostatic pressure (percolation) or under the resultant of gravity and the unbalanced film-pressure (film-flow).

Super-capillary interstice--One larger than a capillary interstice in which water is not held at an appreciable height above a water-table or hydrostatic pressure-level and through which the movement of water may be turbulent.

Sub-capillary interstice--One smaller than a capillary interstice in which molecular attraction spans the entire space and water is held immovable against gravity by the forces of adhesion alone. Such water is essentially pellicular and hygroscopic.

Porosity--The property of a rock or earth of containing interstices. Like interstices it may be continuous or discontinuous, primary or secondary. It is quantitatively expressed as the percentage of the aggregate volume of interstitial space to total volume.

Apparent specific gravity (volume-weight)--The ratio of the weight of a unit volume of oven-dry soil to that of an equal volume of water under standard conditions. This term may be applied either to natural undisturbed field-samples or to reworked laboratory-samples.

Precipitation--The process by which water in liquid or solid state is discharged out of the atmosphere, principally upon a land or water surface. It is the process by which atmospheric water becomes surface or subsurface water. It includes dew, fog-drip, rain, hail, and snow. The term "precipitation" is also used to designate the quantity of water that is precipitated. Rate of precipitation is expressed in depth (measured as liquid water) precipitated upon a horizontal surface at specified location and elevation per unit of time--generally in inches or centimeters per day, month, or year.

Subsurface water

Subsurface water--Water that occurs in the lithosphere. It may be in liquid, solid, or gaseous state. It comprises suspended water and ground-water.

Zone of saturation--The zone of the lithosphere in which the functional interstices of permeable rock or earth are completely filled with water under hydrostatic pressure.

Zone of aeration--The zone of the lithosphere in which the functional interstices of permeable rock or earth are not (except temporarily) filled with water under hydrostatic pressure. The interstices contain water and air, except that smaller ones within the capillary fringe may be filled with water that is held by capillarity. The zone of aeration comprises the belt of soil water, the intermediate belt, and the capillary fringe.

Soil water--Water in the zone of aeration immediately below the surface of the ground, from which it may be discharged into the atmosphere in appreciable quantities by plant transpiration or soil evaporation.

Capillary fringe--The belt of subsurface water overlying the zone of saturation in material having capillary interstices, the smaller of which are filled with water that is continuous with the zone of saturation but held above that zone by capillary forces acting against gravity. Materials having only subcapillary interstices are impermeable and are not regarded as having a capillary fringe. In materials whose interstices are supercapillary, the capillary fringe is practically absent.

Suspended water--Subsurface water partially occupying interstices in the zone of aeration. It comprises hygroscopic, pellicular, mobile, and fringe-water. (Note: Lebedeff excludes fringe-water in his definition of suspended water.)

Hygroscopic water--Suspended water adhering to the surface of solid particles or the walls of fractures which is in equilibrium with atmospheric vapor. It is essentially the water which molecular attraction of solid for liquid can hold against root-absorption and evaporation. It does not move as a liquid but is capable of moving in the form of vapor from areas of greater to lesser moisture. (Note: Veihmeyer points out that this term has no exact meaning since water in field-soils is seldom in equilibrium with atmospheric vapor above ground except in the extreme surface-layer.)

Pellicular water--Suspended water adhering by molecular attraction to the surface of solid particles or the walls of fractures but in excess of hygroscopic water. It is fixed water capable of partial extraction by root-absorption and evaporation, but not moved by gravity or the unbalanced film-forces resulting from localized evaporation and transpiration. Lebedeff states that such water moves very slowly as a liquid from places with thicker film to places with thinner film, probably in response to molecular force. There may also be movement by distillation from surfaces of gentle curvature and condensation upon those of sharp curvature. (Term derived from the Latin word "pellis" meaning "skin"; first used by Lebedeff in the term "pellicule water," and proposed in present form by C. F. Tolman, Department of Geology, Stanford University, California.)

Mobile water--Suspended water occupying films covering the surface of solid particles or the walls of fractures, but in excess of pellicular water. It is free to move in any direction under the pull of the resultant of the force of gravity and unbalanced film-pressure. It is frequently termed "gravity-water" or "free water."

Fringe-water--Mobile water suspended in the capillary fringe above the water-table and completely filling the smaller interstices. It moves with the capillary fringe as the latter rises and falls with the fluctuations of the water-table. When the water-table is shallow, water moves upward from it to replace loss by evaporation and transpiration, being actuated by the resultant force of unbalanced film-pressure minus the downward pull of gravity.

Ground-water--Subsurface water occupying interstices in a zone of saturation. It may be classified as water of saturation, or that which completely fills the interstices of rock, or of earth whose particles are in contact; and as water of supersaturation, or that which is in excess of the water of saturation in earths such as quicksand, plastic clay, or flowing mud, whose particles have lost contact and are more or less separated by water.

Water-table--The upper surface of a zone of saturation except where that surface is formed by an impermeable material. There is no water-table if the upper surface of a zone of saturation is formed by an impermeable body.

Perched water-table--The upper surface of a body of free ground-water in a zone of saturation separated by unsaturated material from an underlying body of ground-water in a differing zone of saturation.

Semi-perched water-table--The upper surface of a body of free ground-water having a greater pressure-head than an underlying body of ground-water not separated from it by unsaturated material and lying within the same zone of saturation. Semi-perched and perched ground-water is supported by semi-permeable or impermeable confining beds.

Movement of subsurface water

Free-surface energy--The free energy in a liquid surface produced by the unbalanced inward pull exerted by the underlying molecules upon the layer of molecules at the surface. For purposes of calculation, a hypothetical tension is assumed acting in all directions parallel to the surface and equal to the free-surface energy. This mathematical equivalent of free-surface energy is termed surface-tension.

The inward pull may also be considered as a pressure acting upon the liquid surface. This surface-pressure differs with differing curvature of the liquid surface. For concave curvature it is less than for a plane surface and decreases with increase in the degree of curvature; for convex curvature it is greater than for a plane surface and increases with increase in the degree of curvature. The rise of water in capillary tubes is caused by the negative difference in surface-pressure of the plane surface of the water outside the tube and the curved surface within. The curvature of the latter is established by the diameter of the tube and the liquid-solid contact-angle.

Film-pressure--The inward pull (or pressure) acting upon the water-air surfaces of a film-system of suspended water composed principally of mobile or fringe-water. These surfaces are curved, with concavity toward the air spaces. The magnitude of film-pressure is controlled by surface-tension and surface-pressure. The magnitude of surface-tension in suspended water is influenced by the chemical character of the soil-solution and the temperature. The magnitude of surface-pressure in suspended water is controlled by the size and shape of interstices between soil-grains as established by soil-texture and structure. In a capillary fringe there is the additional controlling factor of solid-liquid contact-angle.

Film-pressure controls the height of the capillary fringe, the distribution of fringe-water under conditions of equilibrium, and the movement of fringe-water upward from the water-table to replace losses by evaporation and transpiration. Film-pressure also causes the movement of mobile water in the film-system above the capillary fringe. Such movement occurs when film-pressures in adjacent portions of the film-system become unbalanced by local change in water-content with resulting change in surface-curvature. Changes in water-content may result either from addition by infiltration, etc., or from depletion by evaporation, transpiration, etc. The direction of movement is from the area of greater abundance of water to that of lesser abundance. Movement in a given direction continues until either equilibrium is reestablished or a further change in water-content occurs.

Potential--As defined in the science of soil-physics, the work required to move a unit mass against a force from one specified point to another. For saturated soils, both gravitational and pressure potentials are in use. For unsaturated soils within the capillary fringe the term capillary potential is in use, being defined as the work required to move a unit mass of water from the level water-surface against capillary forces in the soil-column to any point of specified distance above the water-surface. As thus defined, it does not include the work done against the force of gravity. The capillary potential is negative.

Film-flow--The movement of mobile suspended water in any direction through a system of interconnecting films adhering to the surface of solid particles or the walls of fractures in the zone of aeration. In a capillary fringe, film-flow may occur through interstices which are completely filled with water. Film-flow is produced by the resultant of the forces of gravity and unbalanced film-pressure produced by differences in curvature of the air-water interface. The latter may result from local loss from films by evaporation and transpiration, from local addition to films by infiltration, or by fluctuation of the water-table. This type of flow is stream-lined, with loss of head varying directly as the velocity (Darcy's law). It has previously been variously termed "capillary migration," "capillary movement," "capillary flow," etc.

Percolation--The movement of ground-water in stream-line flow in any direction through small interconnected and saturated interstices of rock or earth, principally of capillary size. It is produced by hydrostatic pressure due to the elevation (head of position) of the water-table in material which permits free movement in any direction, or to pressure-head under conditions of confinement (artesian pressure). It corresponds with flow in pipes of very small diameter or at very low velocities. In this type of flow, loss of head due to friction varies directly as the velocity (Darcy's law).

The term "percolating water," as used in a legal sense, is limited to diffused ground-water unconnected with a stream or other definite body of water, although it may be tributary to and ultimately reach such. Used in this sense it is distinguished from definitely known underground streams or the subflow of surface-streams. Following the broader hydrologic definitions, however, the latter might be termed either "percolation" or "cavern-flow," depending upon the size of interstices.

Cavern-flow--The movement of water in turbulent flow through large openings in rocks such as caves, or through coarse sorted granular material. It may be produced either directly by gravity, when it corresponds with the flow of water in surface-streams, or by hydrostatic pressure, when it corresponds with the flow of water through pipes. In this type of flow, loss of head due to friction varies approximately as the square of the velocity, but for transitional velocities between upper and lower critical velocity it will vary with a lesser power of the velocity exceeding the first power.

Permeability--The property of a material which permits appreciable movement of water through it when saturated and actuated by hydrostatic pressure of the magnitude ordinarily encountered in natural subsurface-water. As used in ground-water hydrology, rock or earth is considered permeable when appreciable percolation occurs through it. The term "perviousness" is sometimes used in the same sense as permeability.

Impermeability--As used in ground-water hydrology, the property of a rock or earth which does not permit water to move through it perceptibly under the pressure ordinarily found in subsurface water. Certain highly porous materials are subcapillary in size. Bodies of impermeable material, such as impermeable clay, may lie within either the zone of saturation or the zone of aeration, but may not be an active functional part of either zone.

Soil-water

Specific retention--The amount of water retained against the pull of gravity by rock or earth after being saturated and allowed to completely drain to a remote body of mobile water by way of continuous capillary interstices. Meinzer points out that specific retention should be defined in terms of period of drainage. Specific retention is expressed ordinarily as per cent by volume. To fulfil this definition in laboratory tests it is necessary to use a soil-column of height considerably exceeding the height of the capillary fringe, to continue the experiment for extended periods of time, especially when working with fine-textured material, and to provide temperature-control. Standardization of the limiting conditions is one of the serious problems of ground-water hydrology.

Specific retention is sometimes erroneously stated to be synonymous with field-capacity of soils. It is a broader term than "field-capacity," being applied to all types of earth or rock. Its use is to determine the volume of water drained by the lowering of the water-table over a relatively long period of time as a result of pumping operations or seasonal fluctuation. "Field-capacity," on the other hand, is used to determine the amount of water available to plants within a short period after rain or application of irrigation-water, and may indicate the amount of water in the soil before complete drainage has taken place. If accurately determined, specific retention should indicate smaller equivalent values than field-capacity.

Specific yield--The amount of water which a rock or earth will yield after being saturated and allowed to drain under the conditions specified for determining specific retention. It is expressed as per cent by volume. The sum of specific retention and specific yield equals the porosity of the material drained.

Soil-water percentage--This term usually refers to percentage of water in the soil based on the weight of material oven-dried at 110° C. Percentages based on air-dry material or by volume are rarely used in present soil-moisture investigations, as they are not constant values. To convert soil-water percentage to equivalent depth of water, multiply together soil-water percentage, apparent specific gravity of material in place and depth of soil, and divide by 100.

Moisture-equivalent--The amount of water retained by soil placed in a standardized apparatus when the water-content is reduced by means of a constant centrifugal force (1000 times gravity) acting for a specified period or until a state of capillary equilibrium with the applied force is attained. It is expressed as per cent of dry weight. In reporting moisture-equivalent the detail of the procedure should be stated.

Field-capacity--The amount of water retained in the soil after excess mobile water has

drained away and the rate of downward movement has materially decreased following an application of water from rain or irrigation. For more exact definition of the value used for field-capacity the following should be stated: The soil-texture, structure, uniformity and depth, the depth and rate of application of water, the temperature of the water, the degree to which evaporation and transpiration were eliminated in the test, the free-drainage conditions, the depth to the water-table, and the time elapsing after application of water that samples were taken. The length of time for a soil to reach field-capacity varies from 24 to 48 hours in sandy soils, five to ten days in silt-clay soils, and longer periods in clay soils. Field-capacity is usually expressed as percentage of dry weight. The terms "capillary capacity," "maximum water-holding capacity," etc., have been used with essentially the same meaning as "field-capacity." (The term has been developed in soil-water investigations because the term "moisture-equivalent" is not representative of maximum water-content available for plant growth in all soil-types. In view of the fact that slow downward movement continues after field-capacity has been attained, the adoption of this term as a hydrologic term is questioned by some members of the Committee, and its inclusion in this list is tentative pending the availability of some more acceptable term.)

Initial water-deficiency--The amount by which the actual water-content of a given soil-zone (usually the root-zone) is less than field-capacity at the beginning of a rainy season.

Absorption

Absorption--The processes by which air or water enters the lithosphere, the latter either as vapor or liquid. The absorption of water includes (1) inflow of atmospheric water-vapor, (2) hygroscopic adsorption, (3) wetting, (4) infiltration, (5) influent seepage, and (6) gravity-flow of streams into sink-holes or other large openings. Temporarily-absorbed water reaches only the belt of soil-water or the intermediate belt of the zone of aeration, from which it escapes either by evaporation from film-surfaces or by root-absorption and transpiration from vegetation. Permanently-absorbed water passes downward beyond the root-zone, finally reaching the zone of saturation, where it becomes an increment to ground-water. The term "soil-water reject" has also been used in this sense. The term "absorption" is also used to designate the quantity of water absorbed, and is expressed in depth of water (measured as liquid water) absorbed per unit of time--generally in inches or centimeters per hour, day, month, or year.

Wetting--The process by which a liquid is adsorbed by a solid surface forming a liquid film thereon which "wets" the surface. All solids adsorb (or condense) upon their surfaces, gases, or vapors with which they are in contact. For a liquid to wet a solid in the presence of air, it must be adsorbed more strongly than the air and displace it. The same is true in order that a liquid may wet a solid previously wet by another liquid. The ability of a liquid to wet a solid surface is expressed physically by low contact-angle between the liquid and solid surfaces. Wetting to the point of pellicular satisfaction is necessary before film-flow can occur.

Spreading--The process by which a small amount of a liquid, as a drop, when placed upon the surface of another immiscible liquid, or upon a solid which it wets, will spread to a film. Liquids usually spread on solids only through the vapor, by evaporation from a drop and condensation to a film. Water, being relatively non-volatile, spreads very slowly. Spreading is not appreciably involved in the process of absorption.

Infiltration--The absorption of liquid water by a zone of aeration. It includes the formation and upbuilding of surcharged films around soil-grains through wetting by fog-drip, rainfall, melting snow, or temporary sheet-water, and the downward movement of mobile water into the soil by film-flow, trickling or percolation after the demand for pellicular water has been satisfied. It is sometimes erroneously termed "rainfall-penetration."

Seepage--The process by which liquid-water percolates through the surface of the lithosphere from or into a zone of saturation. Influent seepage occurs when a body of surface-water, such as a stream or lake, is in contact with a zone of temporary or permanent saturation extending to the surface of the ground. Effluent seepage occurs at springs or seepages where the surface of a zone of saturation is intersected by the ground-surface.

Rainfall-penetration--The depth below the soil-surface reached by a given quantity of infiltration from rainfall. Under arid and semi-arid climatic conditions, this depth frequently does not extend beyond the root-zone.

Water-spreading--Artificial infiltration or influent seepage produced by spreading of surplus stream-flow over permeable soil by means of ditches, basins, pits, or wells.

Transpiration and evaporation

Evaporation--The process of vaporization at a temperature at or below the boiling point. It is the principal process by which surface or subsurface water is converted to atmospheric water. It takes place whenever water in the liquid or solid state comes in contact with an unsaturated part of the atmosphere. The term "evaporation" is also commonly used to designate the quantity of water that is evaporated. Rate of evaporation is expressed in depth of water (measured as liquid water) removed from a specified surface per unit of time--generally in inches or centimeters per day, month, or year. As thus measured it may be considered as negative precipitation.

Evaporativity--The evaporating power of the atmosphere or the potential rate of evaporation with continuous water-supply. Rate of evaporativity is measured by plant physiologists in terms of weight units of chemically pure water lost per unit of time from some specified standard evaporating surface. For more general but less accurate use it is measured as depth of water removed from such a surface in unit of time.

Relative evaporation--The ratio of the rate of evaporation from a surface in contact with the atmosphere to the evaporativity under the existing atmospheric conditions, or the ratio of the actual to the potential rate of evaporation. When considered for a land-surface, transpiration, if any, is usually included with evaporation.

Interception--The process by which precipitation is caught and held by foliage, twigs and branches of trees, shrubs and other vegetation, and evaporated from these surfaces.

Transpiration--The process by which water-vapor leaves the living plant body and enters the atmosphere. It includes cuticular transpiration, or direct evaporation into the atmosphere from moist membranes through the cuticle; and stomatal transpiration, or outward diffusion into the atmosphere through the pores of stomata and lenticula of water-vapor previously evaporated from imbibed membranes into gas-spaces within the plant.

Consumptive use--The quantity of water per annum used by either cropped or natural vegetation in transpiration or in the building of plant-tissue, together with water evaporated from the adjacent soil, snow, or from intercepted precipitation. It has been variously termed "evapotranspiration," "fly-off," "evaporation," etc.

Retention--The amount of precipitation upon a drainage-area not escaping as surface streamflow. It is the difference between cumulative precipitation and total runoff, and represents evaporation, transpiration, subsurface-leakage, and when short periods are considered, temporary surface- or ground-storage on the drainage-area. It closely represents consumptive use when considered for periods of a year or more.

Runoff

Runoff--That portion of the precipitation upon a drainage-area which is discharged from the area as surface-water in stream-channels.

Surface-runoff--The portion of runoff which is not absorbed or lost by evaporation and interception and flows to stream-channels over the surface of the ground. The usual sources of surface-runoff are rainfall occurring with intensities exceeding the rate of infiltration, and snow upon the ground melting at rates exceeding the rate of infiltration. Surface-runoff is the principal source of flood-flow in streams occurring at times of rainstorm or melting snow. Such flow is variously termed flood runoff, storm-water, etc.

Ground-water runoff--The portion of runoff which is permanently absorbed and after becoming ground-water ultimately discharges into stream-channels as spring and seepage water. Ground-water runoff is the principal source of normal or dry-weather flow of streams unregulated by surface-storage, and such flow is sometimes termed ground-water flow.

Total runoff--The accumulated volumetric runoff from a drainage-area for a definite period of time such as duration of a storm, day, month, or year. Total runoff is expressed by the formula $R = (P - L \pm S)A$, where R is total runoff, P is total depth of precipitation during the period considered, L is the depth of accumulated losses during the period by evaporation from water, snow, ice, and soil, interception, transpiration, and leakage through deep percolation, S is cyclic surface, snow or ground-storage expressed as equivalent depth, and A is the superficial area of the drainage-basin. For short periods, correction for channel- and bank-storage may be necessary.

Maximum flood-flow--The maximum rate of discharge from a drainage-area resulting from rainfall of high intensity or from melting snow. It may be expressed by the formula $Q = CiA$, where Q is the maximum rate of discharge, i is the maximum uniform intensity of rainfall whose duration equals or exceeds the time required for concentration of water from the most remote point (in time) of the drainage-area, C is a runoff-coefficient representing the ratio of the rate of runoff at the end of the time of concentration to the rainfall at maximum uniform intensity during this period, and A is the portion of the superficial drainage-area covered by the storm yielding rainfall of maximum intensity.

REPORT OF THE COMMITTEE ON RAINFALL AND RUNOFF, 1934-35

L. K. Sherman, Chairman

The past year has witnessed an unprecedented amount of statistical and research work in hydrology. This has been due, in a large measure, to a recognition by the Federal Government of the need for an inventory of public natural resources and a policy for their rational use or control. As agencies to this purpose the National Resources Board and the Mississippi Valley Committee were established. Later the duties of this Committee were enlarged to a nation-wide field. The Mississippi Valley Committee then became the Water Planning Committee of the National Resources Board. The United States Geological Survey, Water Resources Branch, with special assistants, was delegated to make studies in hydrology.

At the request of Chairman Morris L. Cooke of the Mississippi Valley Committee, the Section of Hydrology of the American Geophysical Union appointed an advisory group to the United States Geological Survey work on hydrology. This group or Special Advisory Committee consists of W. W. Horner, as Chairman, Robert E. Horton, Adolph Meyer, G. W. Pickels, L. K. Sherman, Roy Towle, and J. W. Woermann. A similar advisory committee, with G. H. Matthes as Chairman, was appointed by the American Society of Civil Engineers. The Advisory Committee of the American Society of Civil Engineers confines itself to flood phenomena. Our Advisory Committee deals with the phenomena relating to rainfall and runoff exclusive of floods. Members of our Committee, especially Chairman Horner and those having occasion to be in Washington from time to time, have kept in contact with the work of the United States Geological Survey through the cooperation of N. C. Grover, in charge. The United States Geological Survey has submitted a number of important hydrologic studies. These include runoff-formulas, analysis of statistics on annual rainfall and runoff, trends by ten-year moving average, effects of temperature-changes, infiltration, use of the hydrograph in the rainfall-runoff relation, segregation of stream-flow into surface-runoff and ground-water flow. Your Advisory Committee has made written suggestions and criticisms of these works together with suggested lines for research. A joint meeting was held with the Committee of the American Society of Civil Engineers last January in New York. On April 23-24, 1935, your Committee met with the United States Geological Survey staff in Washington. Appended is a copy of the report of your Advisory Committee to the Committee of the National Resources Board under date of November 1934 (Appendix D). All of this hydrologic work will be in progress at least until July next. W. G. Hoyt and the United States Geological Survey staff made extensive studies on the use and limitations of the unit-hydrograph method. Thorndike Saville, Chairman, Subcommittee on Statistical Methods, together with H. Alden Foster and United States Geological Survey staff, have made critical studies of various procedures of statistical methods. Their findings are important and should be considered by anyone applying statistical methods to rainfall or runoff.

During the summer and fall of 1934, the National Resources Board, under the direction of Thorndike Saville, made an inventory of the water resources of the entire United States. Naturally most of this relates to economic applications. The inventory does include important hydrologic data and statistics which are in convenient form and not heretofore available. The report of the Mississippi Valley Committee was published under date of October 1, 1934. Report of the Water Planning Committee, National Resources Board, was published under date of November 15, 1934. The latter is included in Part III of the report of the National Resources Board, December 1, 1934. These works show the importance of scientific hydrology in relation to social and economic application. The printed reports are obviously condensed.

Among the important papers relative to rainfall and runoff which have been presented during the past year are the following in Proceedings of the American Society of Civil Engineers: Papers by Bleich, Horner and Flynt, Slade, and discussion of Bernard's paper. Publications include: Report of the International Association of Hydrology, "Excess rainfall in Texas," State Reclamation Department, Austin, Texas; "The hydraulics of flood-movements in rivers" by Harold A. Thomas, Carnegie Institute of Technology; "Surface-runoff phenomena, Part I, Analysis of the hy-

drograph" by Robert E. Horton. The analysis by Horton makes a new and important application of the storage-equation to the rainfall-runoff relation. Your Chairman, therefore, presents a review of Horton's work as Appendix C, entitled "The infiltration-theory of surface-runoff."

The importance of experimental investigations of runoff and infiltration in relation to rainfall is recognized by work started by the Soil Erosion Service, United States Department of Agriculture. During 1934 experimental plots were established in many parts of the country. Your Committee on Runoff, in this report, has attempted to make available the sources where such experimental researches are or where data may be obtained. To this end the accompanying appendices A and B are presented. Appendix A, entitled "The experimental study of runoff," gives a list of some of the data which have been recorded on experimental plots together with our comments relative to such work. On March 25, 1935, your Chairman of the Runoff Committee sent out a circular letter stating that the Committee desired to submit with their annual report a descriptive list of the places where runoff is being measured from experimental plots and requested a brief statement answering the following: Agency; number and size of plots; method of measuring rainfall and runoff; date established; purpose of the experiments and data published. Your Chairman expresses his appreciation of the generous response to this request. These data on experimental plots now in operation are presented in Appendix B entitled "Experimental plots for runoff, in operation or recently established."

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APPENDIX A--THE EXPERIMENTAL STUDY OF RUNOFF

Great activity exists at the present time in the study of the scientific aspects of runoff-phenomena. It is gradually being recognized that the best basis for the study of the laws governing many, though not all, of the phenomena of runoff, particularly surface-runoff, is experiments on small areas where the conditions are or can be fully or partly controlled. Among the advantages of such a small area for the purpose of studying runoff-phenomena or testing the validity of any theory or method in relation thereto are: (1) Such an area provides the possibility of obtaining a single type of fairly homogeneous soil; (2) it provides the possibility of measuring runoff under conditions where the rainfall is continuous at the same time over the whole drainage-basin and where the rainfall regimen during each shower or storm is simultaneous over the whole drainage-basin; (3) it is much easier to obtain an accurate measurement of the actual average rainfall in a given storm than in the case of a larger drainage-basin.

Data of this kind may be obtained in four ways: (1) By laboratory experiment, using sprinkled plats or pans; (2) by the use of overflow-lysimeters, with natural rainfall; (3) by the use of field-plats, with natural rainfall; (4) by the gaging of small drainage-basins.

In spite of the enormous amount of stream-gaging which has been carried out in the United States it turns out that there are comparatively few published examples showing in full detail and accurately the complete course of events with reference to rainfall and runoff from the beginning to the end of the resulting stream-rise. There are, however, at present several series of field and laboratory experiments on runoff being carried out where data such as described and such as are needed in the scientific study of runoff are being or could be collected. Unfortunately at the present time most of these data are obtained primarily for another purpose, that of the study of soil erosion, and either the complete runoff-graphs and accompanying data are not being obtained or, if obtained, are not published. In some instances examples of actual runoff-graphs can be obtained on application. The Committee submits the following list, though by no means complete, of experimental work of this type which is now being carried on or has recently been completed.

Wollny seems to have been the first to study runoff under fully controlled conditions. His experiments, carried out in 1882 and 1883, covered: (a) Three different types of soil, with otherwise similar conditions; (b) calcareous sand with humus, with two different slopes and four orientations, that is, north, east, south, and west; (c) the same soil with grass, and bare, and each with three different slopes, 10°, 20°, and 30°. Wollny's experiments, though little known in the United States, are published in full in "Forschungen auf dem Gebiet der Agricultur Physik" and a translation of these data would seem to be well worth while, even though only daily rainfall- and runoff-data were obtained.

More than 30 years ago R. E. Horton recognized the value of runoff-data from small and simple drainage-basins as a basis of study of runoff-phenomena. Through cooperation with the local

water-supply company he secured the establishment, in 1903, of steel-plate weirs on three small streams near Utica, New York, with drainage-basins of 0.28, 1.18, and 3.4 square miles, respectively. The drainage-basins were adjacent, in the same geologic formation, and with similar soil and vegetational conditions. Several rainfall-stations were maintained and ground-water level records were also kept. Unfortunately, at that time, recording gages were little used and staff-gage readings and daily rainfall-observations were utilized.

In order to supply additional information needed for the most complete interpretation of the results, Graefenburg Hydrophysical Station was established on one of these drainage-basins in 1904. At this station records were kept of evaporation from a United States Geological Survey type, 3-foot-square buried tank, and of the percolation through five lysimeters with different types of soil. In addition, records were kept of soil temperature at 2-inch and 24-inch depths, together with wind-movement, vapor-pressure, air-temperature, water-temperature in the evaporation-tank, and, during the winter, accumulated snow- and water-equivalent. The records in full for both stream-measurements and for the hydrophysical station appear in the annual volumes of the reports of the New York State Engineer and Surveyor, 1903 to 1910, inclusive. While the records as printed contain typographical errors, particularly shifting of decimal points, they give a mass of valuable data. The earlier years of these records were taken with extreme care. The later records suffer for want of adequate inspection.

Taking up first fully-controlled laboratory experiments, but with natural rainfall, José Garcia Montes, C.E., Havana, Cuba, states (by letter dated September 11, 1934):

"With regard to the gaging of rainfall-intensity mentioned in that article (Revista de la Sociedad Cubana de Ingenieros, v. xxvi, núm. 1, Enero-Febrero, 1934, pp. 1-43) I have recently established what I have called an intensity-integrator gage, which is nothing else than a suitable galvanized receptacle 1-1/2 feet in diameter and 2-1/4 feet deep. This is perforated in the bottom and filled to the depth of 1/4 foot with gravel and 2 feet of a standard clay-loam, highly resistant to erosion, as is frequent with many tropical soils. A surface-overflow directs surficial runoff to another receptacle and the amount percolating is also measured. The gage is operated in connection with a standard rain-gage. From a measurement of the amount percolated and running off the surface, a relative measure of the intensity is secured. I have operated the apparatus only a few months but some interesting results have been obtained. The advantage of the apparatus is, I believe, that it measures the intensity micrometrically, it can be said, and, moreover, in a certain sense, it gages also the effect of other climatic influences in that connection. The apparatus is cheap and it effectively tackles the naughty intensity question in connection with water-losses to agriculture."

An apparatus similar to that described by Montes is essentially an overflow-lysimeter. It possesses important possibilities for the experimental study of runoff-phenomena if accompanied by a recording rain-gage and if the surface-runoff and percolation are also measured by a recording gage. Such a gage can be obtained with two pens, which will record both the surface-runoff and percolation on one sheet. Montes calls this a "rainfall-integrator." More properly, it is a "rainfall-analyzer," since it separates the rainfall into its two main components--surface-runoff and infiltration. Furthermore, it separates the infiltration into its two components--accretion to soil-moisture and percolation to ground-water. Since the infiltration-capacity of a soil varies with the soil-type, it is obvious that a given apparatus will determine the disposal of rainfall only with reference to the type of soil which it contains. Several sets of apparatus can, however, easily be maintained with different types of soil, and the Committee suggests that this type of apparatus might well be substituted for non-overflow lysimeters now in use at various locations.

Brief digression at this point with reference to the use of lysimeters is pertinent. Lysimeter-installations were much the vogue in England, and, to a lesser extent, in the United States in the nineteenth century. Their use has been revived in the United States and there are now or recently have been several extensive and excellent series of non-overflow lysimeter records maintained, including the following: Cornell University, Ithaca, New York; Geneva Agricultural Station, Geneva, New York; Virginia Agricultural Station, Blacksburg, Virginia; Connecticut Agricultural Station, New Haven, Connecticut; Illinois Agricultural Station, Urbana, Illinois; and Missouri Agricultural Station, Columbia, Missouri. The Chairman of the Committee would like to be advised of other lysimeter-installations.

It has not generally been recognized that a lysimeter, because of the fact that no provision is made for overflow, does not measure the amount of accretion to the water-table nor the water-losses which take place under natural conditions in the region where the lysimeter is located. More nearly it measures the water-losses and ground-water accretion which would take place in

the same region if the rainfall was increased to an amount equal to the existing rainfall plus the existing surface-runoff.

Nevertheless, lysimeter-records may be of great utility in the study and interpretation of runoff-phenomena. Particularly they serve as an aid in the analysis of the hydrograph in picking off the different types of stream-rises in drainage-basins where part of the flow is derived from ground-water, since if a lysimeter-record such as described shows no percolation in a given rain, it is certain that no accretion to the water-table would occur under natural conditions. Furthermore, they furnish a basis for determining the relative water-losses from different types of soil and with different classes of vegetation.

Runoff from experimental plats--Among publications containing in some form the results of runoff-plat experiments are the following:

Duley and Miller, Erosion and surface-runoff under different soil-conditions, Res. Bull. 63, Agric. Exp. Sta., Univ. Mo., December 1923.
Duley and Ackerman, Runoff and erosion from plots of different lengths, J. Agric. Res., v. 48, No. 6, March 15, 1934.
Conner, Dickson, and Scoates, Factors influencing runoff and soil-erosion, Bull. 411, Texas Agric. Exp. Sta., March 1930.
W. C. Lowdermilk, Studies of the role of forest-vegetation in surficial runoff and soil-erosion, Agric. Eng., v. 12, No. 4, pp. 107-112, April 1931.
W. C. Lowdermilk, Influence of forest-litter on runoff, percolation, and erosion, J. Forestry, v. 28, No. 4, pp. 474-491, April 1930.

Each of the publications referred to contains a description of the runoff-plats and a summary of the results by months or seasons but unfortunately none of these publications gives actual hydrographs and rain-graphs for the individual storm-periods.

Runoff from small drainage-areas--The mimeographed reports of the United States Bureau of Public Roads drainage-investigations contain a large amount of valuable data regarding the sequence of phenomena of runoff and rainfall on small areas. Reference is made to the following reports in particular.

List of runoff investigations made by Division of Drainage and Soil Erosion Control, Bureau of Agricultural Engineering, United States Department of Agriculture, giving dates and extent of investigations

Alabama

Runoff investigations, Catoma Creek, Montgomery County, Alabama, May 1921 to July 1922, by Guy A. Hart. Rectangular area 15 by 22 miles; area of watershed 285 square miles.
Runoff investigations, Luxapallila River, Fayette and Lamar Counties, Alabama, 1923, by P. T. Simons. Drainage-area 142 square miles and 245 square miles; long, narrow watersheds.

Arkansas

Runoff in Cache River Valley of northeast Arkansas, by B. S. Clayton, 1921 to 1923. At Stonewall, drainage-area 32 miles long, about 8-1/2 miles wide, total 272 square miles; at Sedgwick, drainage-area 622 square miles, of which 110 square miles were hill-land; at Jelks, drainage-area 855 square miles; at Black River, drainage-area 1725 square miles.
Runoff of Boggy Bayou District, Desha County, Arkansas, by D. L. Yarnell, 1911. Watershed-area, 165 square miles; measurements made in 1911.
Runoff measurements in northeast Arkansas, by O. G. Baxter. Gagings on Little River and St. Francis River during spring of 1915.

Florida

Runoff investigations on certain Florida East Coast drainage-districts, by Chas. W. Okey (1916), F. E. Staebner (1916 and 1917), A. O. Kay (1923). Records from districts of 15,645, 42,170, and 50,240 acres.

Illinois

Runoff investigations on Sugar and Bay Creeks in southern Illinois, by C. E. Ramser, 1925 to 1927. Sugar Creek watershed, fan-shaped, contained about 20 square miles; Bay Creek had watershed of 148 square miles.
Cost of pumping for drainage in the upper Mississippi Valley, by John G. Sutton; Technical Bulletin 327 and six progress-reports. Runoff records obtained from 17 drainage pumping districts extending over a period of six years, 1925 to 1930; districts studied were bottom lands along Upper Mississippi and Illinois River and watershed-areas ranged from 6760 to 52,000 acres.

Illinois--Continued

Runoff investigations in central Illinois, by Ramser and Norton, 1924 to 1927. Measurements were made on seven streams draining areas of 4.66 to 63.2 square miles, forming headwaters of Kaskaskia River system; on three streams draining watersheds 3.91 to 60.5 square miles of Big Vermilion River system; two stations were located on Embarrass River at points draining areas 27.2 and 718 square miles and one drainage-ditch draining 15.3 square miles flowed into Sangamon River.

Rate of runoff and efficiency of drainage-ditches and tile-drains in corn belt of Illinois and Iowa, 1908, by L. L. Hidinger Watersheds ranged from 21,000 acres to 128,000 acres in Vermilion River; drainage-district and other ditches measured.

Iowa

Runoff investigations on Boyer River and on Allen, Willow, and Pigeon creeks in western Iowa, 1916-1917, by C. E. Ramser. Runoff obtained from watersheds of 59, 143, 148, 654, and 900 square miles; timber land about 5 per cent of total area.

Runoff of Ralston Creek, Iowa, 1923 to date, by D. L. Yarnell. Intensive and detailed investigation on small watershed of 3.03 square miles.

Studies on the maximum rates of runoff from small drainage-areas in Iowa, by F. W. Hawthorne and M. K. Reed, Iowa State College. Investigated five watershed-areas ranging from 187 to 2000 acres.

Louisiana

Runoff and cost of operation of pumping plants in southern Louisiana, 1914-1918, by Okey, Kirschner, and Jones. Runoff obtained from 10 drainage pumping districts of Louisiana ranging in area from 647 to 7400 acres and from one district with watershed-area of 37,750 acres.

Minnesota

Runoff investigations in Murray County, Minnesota. Runoff records for part of 1920 from three tile-drained watersheds ranging from 338 to 2430 acres, and five larger watersheds of 16,300 to 95,730 acres.

Progress-report on runoff investigations and determination of the roughness-coefficient in Kutter's formula in northwestern Minnesota, by Guy L. Smith. Records during 1920 on four flat watersheds ranging in size from 88 to 291 square miles and all having an average length about five times the average width, and on one watershed of 1010 square miles averaging 20 by 53 miles.

Mississippi

Report on runoff investigations and determination of the roughness-coefficient for Kutter's formula in Bolivar County, Mississippi. Runoff measured during 1914 and 1915 from five watersheds ranging from 13.0 to 323.2 square miles in area; measurements made on some areas as later studied in 1923 to 1927, but when 35 to 80 per cent of the areas had been cleared and put into cultivation.

Progress-report on runoff investigations in Bolivar and Washington Counties, Mississippi, by Ramser and Clayton, 1923 to 1927. Typical watershed-soils were one-third sandy loam and two-thirds clay; slope about a foot to mile; most of drainage-areas 80 to 90 per cent cleared and cultivated; measured runoff from seven watersheds ranging from 10.8 to 463 square miles.

Report on runoff of Big Black River at West and Edwards, Mississippi, by A. G. Hall. Report of seven current-meter measurements, March and April, 1914, during flood-stages; watershed-areas of 868 and 2875 square miles.

Runoff of drained areas in Coahoma County, Mississippi, by C. W. Okey, Drainage Engineer, in 1911. Measurements from two drainage-districts of 5300 and 14,800 acres, respectively.

Runoff investigations and determinations of the roughness-coefficient for Kutter's formula made in Lee County, Mississippi, during 1913 and 1914. Measurements were made of the flow in five dredged ditches that furnished drainage for areas of 56 to 140 square miles; uplands are rolling and 20 to 50 feet higher than river bottoms and are largely cultivated.

Relation between precipitation and runoff in the Tallahatchie Drainage District, Yazoo Delta, Mississippi, by C. W. Okey. Measurements of runoff during the period from 1908 to 1911 on four watersheds of 90, 1007, 1815, and 7270 square miles.

North Carolina

Report of runoff investigations and determinations of roughness-coefficient for Kutter's formula in Back and Jacob Swamp Drainage District, Robeson County, North Carolina, 1914 and 1915, by A. D. Morehouse. Measurements of runoff from 14 watersheds of 160 to 22,410 acres.

North Carolina--Continued

Progress-reports on soil-erosion and runoff experiments at North Carolina Experiment Station Farm, Raleigh, North Carolina from June 1, 1924 to May 31, 1929. Runoff from small plots, average width about 6 feet and 75 to 375 feet long; rainfall and runoff were determined very accurately.

Runoff investigations on Third Creek, Iredell County, North Carolina, report by F. O. Bartel. Accurate measurements of rainfall and runoff obtained from watershed-area of 44,083 acres for approximately 10-1/2 years, from 1913 to 1923.

Oklahoma

Progress-report on engineering experiments at soil-erosion farm near Guthrie, Oklahoma, 1931, by C. E. Ramser. Accurate measurements of rainfall and runoff from numerous terraced and unterraced areas, usually between one and five acres in size.

South Carolina

Runoff in Four Hole Swamp, Dorchester, Berkeley, Orangeburg, and Calhoun Counties, South Carolina, by F. G. Eason. Measurements during 1915 to 1917 were made of runoff from swampy area of 600 square miles; watershed, 46 miles long and about 13 miles wide; 30 per cent of watershed cultivated; an undrained swamp down the center varied from a few hundred feet to 2 miles in width.

Tennessee

Runoff from small agricultural areas near Jackson, Tennessee, by C. E. Ramser. Detailed studies of runoff during 1918 from six watersheds ranging in size from 1-1/4 to 112 acres (report published).

Runoff investigations and determination of roughness-coefficient in Kutter's formula for dredging ditches in western Tennessee, by C. E. Ramser and H. S. Andrews. Measurements of runoff obtained during 1916 and 1917 from seven watershed-areas ranging from 6 square miles to 704 square miles; watershed-areas varied from creek bottom-land reclaimed by dredged ditches to very steep uplands, badly eroded, with the steepest slopes ranging from 15 to 40 per cent; silt and silt-loam soils predominate.

Texas

An analysis of drainage-discharge of the Rio Grande project, by R. A. Hart. Runoff data from 23 drains obtained during 1923 and 1924; tiles ranged in length from 5.1 miles to 33.8 miles; tributary area drained by all tiles was 157,100 acres in 1923 and 167,000 acres in 1924.

Utah

Report of technical investigations in Utah by Hart and Margetts made during 1915 and 1916. Data relating to effectiveness of drains, drainage-runoff, and removal of harmful salts obtained on six tracts of land.

Washington

Progress-report on runoff from drainage-systems in Yakima County, Washington, by L. T. Jessup, 1926. Runoff measurements were taken during several years, a large number of ditches draining from 0.28 to 17.19 square miles; measurements usually taken once a month during irrigating season and less frequently during non-irrigating season.

Wyoming

A study of the drainage-discharge in the North Bench Drainage District, Basin, Wyoming. During 1922 and 1923, weekly weir-measurements obtained measuring flow from 3383 acres; district drained by 8.5 miles of tile ranging in diameter from 8 inches to 24 inches laid at an average depth of 9 feet and about 3/4 mile of open ditch.

List of published bulletins containing data relating to runoff

Department Bulletin 652, The wet lands of southern Louisiana and their drainage, C. W. Okey, 1918.
Department Bulletin 832, Flow of water in dredged drainage-ditches, C. E. Ramser, 1920.
Department Bulletin 1456, Drainage by means of pumping from wells in Salt River Valley, Arizona, J. C. Marr, 1926.
Technical Bulletin 129, Flow of water in drainage-channels, C. E. Ramser, November 1929.
Technical Bulletin 184, Erosion and silting of dredged drainage-ditches, C. E. Ramser, June 1930.
Technical Bulletin 327, Cost of pumping for drainage in the upper Mississippi Valley, John G. Sutton.

In most cases hydrographs of original storms and accompanying detailed rain-intensity graphs have not been published but are presumably in existence in the official files in Washington. It would seem well worth while that the better-determined graphs obtained in these investigations should be published.

One published paper, Runoff from small agricultural areas, by C. E. Ramser (J. Agric. Res., v. 34, No. 9, May 1, 1927), contains a considerable number of hydrographs and rain-intensity graphs but unfortunately on so small a scale as to be unsatisfactory for practical use.

Particular attention is directed in this connection to the Final report on runoff investigations in central Illinois, prepared by the United States Bureau of Public Roads in cooperation with the University of Illinois (mimeograph, Washington, 1931), and the published report of the same investigation, Runoff investigations in central Illinois, by George W. Pickels (Bull. Univ. Ill., v. 29, No. 3, Sept. 8, 1931). These two reports contain extensive, complete, and valuable recording rainfall- and runoff-records on several small adjacent drainage-basins under very favorable conditions. Mass diagrams of rainfall and runoff and of small-scale hydrographs are given for all the drainage-areas for the four years covered by the records.

Other runoff experiments from plats and small drainage-basins by non-government agencies include the following: The paper, Measurement of runoff and soil-erosion by a single investigator, by J. E. Weaver and William Noll (Ecology, v. 16, No. 1, pp. 1-12, Jan. 1935), describes a buried catch-tank placed at the downstream end of a sloping runoff-plat 3 feet wide and 33.3 feet long, used by the authors for measuring direct surface-runoff. Results of experiments with this apparatus in different storms and for different types of soil and vegetation are described. In addition, sprinkler experiments were made on the same plats. The authors describe this apparatus as an "interceptometer." This is unfortunate since the term "interceptometer" is already in use to describe an apparatus for measuring the amount of rainfall intercepted by the leaves and branches of vegetation and which, consequently, does not reach the ground directly. To be of the greatest service an apparatus such as that of Weaver and Noll should be equipped with a recording water-level indicator as well as a recording rain-gage.

The Horton Hydrological Laboratory at Voorheesville, New York, has maintained since October 1930 a runoff record on LaGrange Brook, with a drainage-area 36 acres. A steel-plate V-notch weir is used, together with a water-stage recorder; a Friez tipping-bucket rain-gage and a standard United States Weather Bureau rain-gage are operated in summer and a snowboard record is kept in winter. Ground-water level records are maintained at three stations in the drainage-basin. A Class A, United States Weather Bureau evaporation-station is also maintained. A considerable number of complete and well-defined graphs of stream-rises, with accompanying rainfall-data, have been obtained and are being compiled for publication.

The United States Weather Bureau and United States Forest Service Wagon Wheel Gap experiments (October 1910 to September 1926) were conducted under such conditions as to afford a large number of excellent runoff and rain-intensity graphs, accompanied by unusually complete data as to the attendant conditions--evaporation, soil-moisture, etc. The published reports--Supplement No. 17 (1922) and Supplement No. 30 (1928) of Monthly Weather Review--do not contain even the daily rainfall and runoff data. It would be well worth while to have runoff-graphs and rain-intensity graphs plotted from the original data for all principal stream-rises covered by these records and the results published.

The United States Geological Survey has in its files the data adequate for plotting runoff graphs for a large number of stream-rises and floods on small and simple drainage-basins. Usually these data are not accompanied by rain-intensity data.

The Committee desires to suggest that, wherever practicable, runoff graphs on a working scale should be compiled and published, together with rain-intensity graphs for the same storm and area, either derived from nearby United States Weather Bureau recording rain-gages, or that recording rain-gages should be established in conjunction with a number of small drainage-basins on which recording-gage runoff-records are maintained.

In conclusion, it cannot be emphasized too strongly that the data needed and most useful in the study of runoff phenomena are complete runoff-graphs of stream-rises, together with complete rain-intensity graphs in full detail, covering in each instance the full period from the beginning of rain to the end of surface-runoff, and on a sufficiently open time-scale so that time intervals can be read accurately to at least one minute for small areas and to five or ten minutes for larger areas.

It would seem well worth while that the collection and preparation of such data should be made a regular part of the hydrological service of the Federal Government and that a Water Supply Paper or other suitable publication should be devoted to such data.

APPENDIX B--EXPERIMENTAL PLOTS FOR RUNOFF IN OPERATION OR RECENTLY ESTABLISHED

(1) United States Geological Survey

California--Mokelumne Basin. Period 1926-1933. See United States Geological Survey Water Supply Paper 619, pp. 194-195. L. Standish Hall, Chief Hydrographer, East Bay Municipal Utility District, Oakland, California.

(2) United States Geological Survey, Division of Ground Water

Virginia--Difficult Run. One to 57 square miles. December 1934 to date. Purpose: Study of channel storage-method of determining ground-water runoff. O. E. Meinzer, in charge Division of Ground Water.

(3) Bureau of the Metropolitan (Water) District (Hartford, Connecticut)

Connecticut--(1) West Branch of Farmington River, 231 square miles; (2) East Branch of Farmington River, 47.4 square miles; (3) Nepaug River, 23.9 square miles; (4) Phelps Brook, 2.9 square miles; and (5) Clear Brook, 1.0 square mile. West Hartford since 1868; others 1912 to date. Purpose: Development of municipal water-supply. Caleb Mills Saville, Chief Engineer.

(4) United States Geological Survey and Department of Conservation, New York State

New York--

Stream	Location	Approx. drainage-area sq.mi.	Date established
Shackham Brook	Near Truxton, New York	3.5	Nov. 26, 1932
Sage Brook	Near South New Berlin, New York	0.5	Nov. 29, 1932
Cold Spring Brook	China, New York	1.5	Oct. 24, 1934
Lost Nation Brook	Near Centerville, New York	1.5	Oct. 20, 1934

Also letter of C. S. Jarvis, Washington, D. C. Purpose: Influence of reforestation on runoff and soil-erosion. Arthur W. Harrington, District Engineer, United States Geological Survey, Albany, New York.

(5) University of Illinois

Illinois--Big Muddy and others. Purpose: Flood-flow analysis. G. W. Pickels, University of Illinois, Urbana, Illinois.

(6) W. W. Horner, Consulting Engineer, St. Louis, Missouri

Missouri--St. Louis, small sewered areas (see Proc. A.S.C.E., October 1934). Also experimental plots with artificial rain at St. Louis and Dallas, Texas (see Municipal and County Engineering). Purpose: To determine the relation between precipitation, infiltration, surface-storage, and runoff for particular soils and surface-slopes.

(7) University of Iowa and Bureau of Agricultural Engineering, United States Department of Agriculture

Iowa--Ralston Creek, Johnson County, three square miles. 1923 to date. Not published. D. E. Yarnell (Iowa City, Iowa) and Adolph Meyer (Consulting Engineer, Minneapolis, Minnesota). "The Bureau of Agricultural Engineering was formerly conducting measurements of runoff at the soil-erosion experiment stations. On April 1 all the stations were transferred to the Soil Erosion Service of the Department of Agriculture. No results of measurements have been published but information relative to the experimental work can be obtained from C. E. Ramser, Senior Drainage-Engineer, Soil Erosion Service, Washington, D. C. During past years this Bureau conducted runoff investigations in a number of localities. We are enclosing a list of the investigations for which reports have been prepared." S. H. McCrory, Chief of Bureau, Bureau of Agricultural Engineering, Washington, D. C.

(8) Bureau of Water Works and Supply, City of Los Angeles, H. A. Van Norman, Chief Engineer

California--"Fifty plots one square foot in area have been run to date. A few additional will be made in the near future. Volumetric measurements are made during a unit of time by means of graduates. The rainfall is applied by means of various sized sprinklers on the end of a short hose and manually distributed. Tests have been carried on since summer of 1934 on various plots. Individual plot is abandoned at completion of test which may be of one or two days' duration. These tests are made for the determination of reservoir protection from runoff contributed by the watershed. All of our reservoirs are for the purpose of storing imported water. No data have been published." D. A. Lane, Assistant Engineer.

(9) Los Angeles County Flood Control District, California Forest Experiment Station, and City of Oakland

California--"Los Angeles County Flood Control District, 205 South Broadway, Los Angeles, California, has made runoff tests with small experimental plots one square foot in area, at 79 different plot-locations, artificial rainfall being applied. This work was done during the years 1930 to 1934 for the purpose of establishing runoff coefficients for mountain watersheds. A descriptive report of this work was presented at a conference recently held in Los Angeles by the Water Conservation Committee, Division of Irrigation, American Society of Civil Engineers, of which A. L. Sonderegger, 925 Central Building, Los Angeles, is chairman, and I am a member. The Committee hopes to publish this report in the near future. The City Engineer of the City of Los Angeles has made tests similar to those described above in connection with storm-sewer design, and has also established a permanent plot of several acres in extent under the direction of L. W. Armstrong, Engineer of Storm Drains, City Hall, Los Angeles, California. Report of this work was also presented at the Water Conservation Committee conference.

"California Forest Experiment Station is conducting very exhaustive rainfall runoff observations at San Dimas Canyon near Los Angeles, California, where approximately $500,000 is being spent in installation of measuring devices, observational work, etc. The installation work was completed last year, and the experiments are expected to run about ten years. You can obtain information regarding this from Edward Kotok, Director, California Forest Experiment Station, Berkeley, California.

"Walter N. Frickstad, City Engineer, City Hall, City of Oakland, California, is making measurements of rainfall and runoff on hilly watersheds back of the City of Oakland, from which flood runoff issues at time of storm. These measurements have been carried on for several years in connection with storm-drain design, having been initiated at my recommendation as engineering consultant. Details regarding the work could be obtained from the City Engineer." Chas. H. Lee, Consulting Engineer, San Francisco, California.

(10) Bureau of Engineering, City of Los Angeles, California, and Los Angeles County Flood Control District (courtesy of A. L. Sonderegger, Consulting Engineer, Los Angeles, California)

California--"(1) Agency: Storm Drain Division, Bureau of Engineering, City of Los Angeles, California. (2) The number and size of plots: Nine 10 feet by 10 feet; twenty 21-1/2 inch diameter circle; sixteen 15-1/4 inch diameter circle. (3) Rainfall and runoff were measured volumetrically. (4) The experiment was established December 2, 1931. (5) The experiments form part of a general survey of storm-drain runoff conducted to derive a method of computing runoff for local conditions. An interim report, which will cover the experiments on small plots, is being prepared by W. I. Hicks and H. W. Fraim of my organization for submission to the American Society of Civil Engineers. It is hoped that this report will be ready this summer. A short digest of this report was presented at a meeting in Los Angeles March 13 and 14, 1935, sponsored by the Water Conservation Committee of the Irrigation Division, American Society of Civil Engineers, under the auspices of the Los Angeles Section." L. W. Armstrong, City Engineer's Office, Los Angeles.

California--"(1) Agency: Los Angeles County Flood Control District. (2) Number and size of plots: Seventy-five 1-square-foot plots and four 6-square-foot plots. (3) Method of measuring rainfall and runoff: (a) Intensity of rainfall measured by amounts of water poured into sprinkling container each minute; (b) intensity of runoff measured by timing 10-cc increments of runoff as collected in a graduate below the plot. (4) Date established: The first work on square-foot plots was started in September 1930; an investigation of one- and six-square-foot plots has been carried on intermittently to date. (5) Purpose of experiments, data published, etc.: The District's purpose in testing these plots is to obtain the relation between intensity of rainfall and intensity of runoff to the extent that coefficient-curves may be drawn showing the variation of coefficient of runoff with intensity of rainfall on various soil-types and with varying degrees of litter and grass-cover; in the main, the work has been carried on in the canyons of the Sierra Madre Mountains in Los Angeles County, California. No published data on the plot-test are now available. It is understood, however, that a resumé of the writer's paper covering the subject presented before the Water Conservation Conference in Los Angeles on March 13 and 14, 1935, will be printed shortly.

"The Flood Control District is very much interested in the relation of runoff-intensity to rainfall-intensity and would consider it particularly fortunate if the National Research Council should find it feasible to collect and publish recent pertinent data on this subject." Finley B. Laverty, Chief Hydraulic Engineer, Los Angeles County Flood Control District.

(11) United States Geological Survey

California--"During the past season J. Q. Peterson and myself have prepared a report on the New Year's Flood (of 1934) in the La Canada Valley near Los Angeles. We have made use of the data furnished by the Storm Drain Division of the City Engineer's office from two plots of 100 square feet each. Two plates (Figs. 1 and 2) from this report, showing the results of these

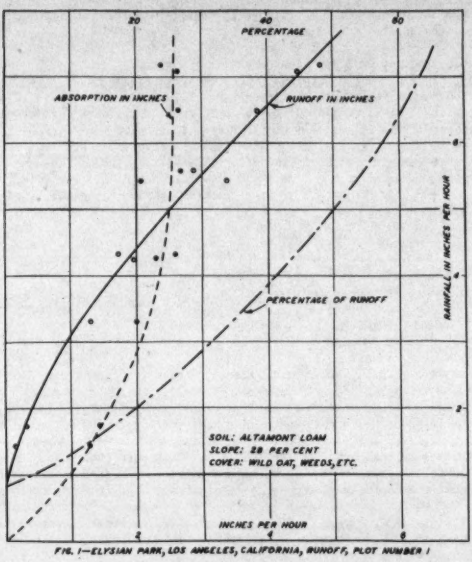

FIG. 1—ELYSIAN PARK, LOS ANGELES, CALIFORNIA, RUNOFF, PLOT NUMBER 1

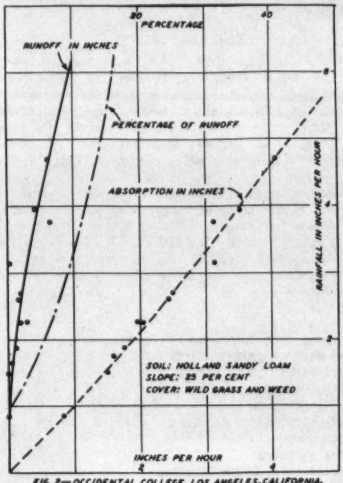

FIG. 2—OCCIDENTAL COLLEGE, LOS ANGELES, CALIFORNIA, RUNOFF, PLOT NUMBER 7

data, are presented herewith." Harold C. Troxell, Associate Hydraulic Engineer, United States Geological Survey, Los Angeles, California

(12) Bureau of Soil Erosion, United States Department of Agriculture

Iowa, Kansas, Missouri, North Carolina, Ohio, Oklahoma, Texas, Washington, and Wisconsin--"(1) Agency: United States Department of Agriculture, Soil Erosion Service. (2) Control-plot set-up at all stations: (A) Short plot 6 feet by 36.3 feet, 1/200 acre (one at each station except Bethany, Missouri); (B) long plot 6 feet by 145.2 feet, 1/50 acre (one at each station); (C) normal plots 6 feet by 72.6 feet, 1/100 acre; (D) desurfaced plots 6 feet by 72.6 feet, 1/100 acre (one to three at each station; surface-soil completely removed).

Station	Number of control-plots	(4) Date established
Guthrie, Oklahoma	13	July 1929
Temple, Texas	11	Jan. 1930
Hays, Kansas	10	Jan. 1930
Tyler, Texas	21	Oct. 1930
Bethany, Missouri	10	Aug. 1930
Statesville, North Carolina	12	Jan. 1931
Pullman, Washington	24	July 1931
Clarinda, Iowa	9	Nov. 1931
LaCrosse, Wisconsin	14	July 1932
Zanesville, Ohio	17	July 1933

(3) Methods of measuring rainfall and runoff: All soil and water caught in large tanks at the foot of the slope. Rainfall is measured in standard Weather Bureau rain-gages. Automatic recording-gages at all stations measure rainfall duration and intensity. (5) Purpose of experiments: To determine methods of controlling soil-erosion and conserving moisture under various conditions of soil, climate, and topography. Data published: The only complete set of data is in the form of annual reports from each station, which have not been published. Many popular articles and a few scientific papers have been published dealing with certain phases of the investigations. A very complete analysis of the soils together with some runoff and erosion data have been published in United States Department of Agriculture Technical Bulletins 316, 430, and 461." H. H. Bennett, Chief of Bureau, Soil Erosion Service, Washington, per R. V. Allison.

Indiana, Pennsylvania--See letter on file from Austin L. Patrick, Regional Director, United States Soil Erosion Service.

South Carolina--Spartansburg, September 1934. Size 1/200 to 1/100 acre. T. S. Buie, Regional Director, for H. H. Bennett, Chief.

(13) Soil Erosion service

New York--Arnot Forest, Ithaca, New York. Sixty-nine plots. Size 1/200 to 1/2 acre. Slope 10 per cent. Volumetric measurements. Purpose: To study effect of vegetation and runoff and soil-erosion. Established 1934.

Pennsylvania--State College. Twenty-eight plots. Size 1/100 to one acre. Slopes 4 to 20 per cent. 1934 to date. Purpose: To study effects of vegetation on runoff and erosion.

New Mexico--Mexican Springs, near Gallup. Eighteen plots. Size 1/10 to 3 acres. Slopes 3 to 5 per cent. 1934. Purpose: Effect of grazing, length of plots on runoff and erosion. No data yet.

"I am herewith enclosing a descriptive list of experimental runoff-plots installed by the Soil Erosion Service together with a brief description of other work carried on by the Service which may be of interest to your Committee. . . . . A list of agencies engaged in runoff-plot studies is hereto attached; by addressing them directly you may get a good deal of first-hand information." W. C. Lowdermilk, Vice-Director, Soil Erosion Service, Washington, D. C.

(14) United States Geological Survey

North Carolina, High Point--

"Drainage-areas above gaging-stations	Sq. mi.
West Fork of Deep River near High Point, North Carolina	33
East Fork of Deep River near High Point, North Carolina	13.9
Deep River near Randleman, North Carolina	124.0
Uharie Creek near Trinity, North Carolina	11.3
Muddy Creek near Archdale, North Carolina	14.2
Horsepen Creek at Battleground, North Carolina	15.9

South Carolina, Spartansburg--

"Drainage-areas above gaging-stations	
South Tiger River near Reidville, South Carolina	106
South Tiger River near Woodruff, South Carolina	174
North Tiger River near Moore, South Carolina	162
Tiger River near Woodruff, South Carolina	351

Wisconsin, LaCrosse--

*Drainage-areas above gaging-stations	Sq. mi.
Coon Creek at Coon Valley, Wisconsin	77.2
Coon Creek near Stoddard, Wisconsin	119.0
Little LaCrosse River near Leon, Wisconsin	77.1

Missouri, Tarkio--

*Drainage-areas above gaging-stations	
West Tarkio Creek near Westford, Missouri	127
East Tarkio Creek at Blanchard, Iowa	200
East Fork of Big Creek near Bethany, Missouri	95

Kansas, Mankato--

*Drainage-areas above gaging-stations	
East Limestone Creek at Ionia, Kansas	51.6
East Limestone Creek 2 miles north of Ionia, Kansas	23.7
Elm Creek near Ionia, Kansas	23.2
West Buffalo Creek 1 mile northwest of Jewell, Kansas	15.3
West Buffalo Creek at Jewell, Kansas	16

Oklahoma, Stillwater--

*Drainage-areas above gaging-stations	
Stillwater Creek near Stillwater, Oklahoma	165
West Fork of Brush Creek near Stillwater, Oklahoma	13.1
Council Creek near Stillwater, Oklahoma	30.2

Texas, Temple--

*Drainage-areas above gaging-stations	
Big Elm Creek near Temple, Texas	68.5
Big Elm Creek near Buckholts, Texas	166.0
Deer Creek near Chilton, Texas	81.8
North Elm Creek near Ben Arnold, Texas	29.2

Washington, Pullman--

*Drainage-areas above gaging-stations	
South Fork Palouse River above Missouri Flat Creek at Pullman, Washington	131.96
South Fork Palouse River above Paradise Creek near Pullman Junction, Washington	81.12
Missouri Flat Creek at Pullman, Washington	27.52
Fourmile Creek at Shawnee, Washington	73.06
Dry Fork of South Fork of Palouse River at Pullman, Washington	7.42
Paradise Creek near Pullman, Washington	37.02

"The final computations and analyses of the records have not yet been completed but I am sending you herewith statements in regard to the work which is being done and information regarding the equipment and methods employed." Observation-wells in connection with the foregoing stations. C. H. Pierce, Member, Committee on Runoff, Section of Hydrology.

(15) United States Geological Survey

Missouri--"This office is collecting continuous records of runoff from three experimental plots in northwestern Missouri and southwestern Iowa, in cooperation with the United States Soil Erosion Service, as follows:

Stream	Location	Date established	Drainage-area in sq. mi.
East Fork of Big Creek	Bethany, Harrison County, Missouri	March 9, 1934	95
West Tarkio Creek	Westboro, Atchison County, Missouri	March 14, 1934	127
East Tarkio Creek	Blanchard, Page County, Iowa	March 13, 1934	200 *

H. C. Beckman, District Engineer, Rolla, Missouri.

(16) United States Geological Survey for Soil Erosion Service

Texas, Tyler--Soil-erosion experiment station No. 4. Includes four projects and 33 plots. Size of plots 1/200 to 1/20 acre. Date established: Thirteen in 1931, others in 1932-34. Published: Annual reports Texas Agricultural Experiment Station, 1931-34.

Texas, Temple--North Elm Creek 29.2 square miles. Big Elm Creek 68.5 and 166 square miles. Check on Deer Creek 81.8 square miles. Established 1931. Slope 4 per cent. Ground-water elevation from 19 wells. (Chairman, Runoff Committee, American Geophysical Union, has additional data.) John W. Pritchett, State Board of Water Engineers, Austin, Texas.

(17) Illinois State Water Survey

Illinois--Studies being made since 1929 on six artificial lakes for domestic water-supply.

Location	Area of district in acres	Water-surface in acres	Storage in millions of gallons
Lake Bracken, near Galesburg, Illinois	7000	195	950
Near Bloomington, Illinois	38400	530	2250
Near Staunton, Illinois	2560	105	382
Near Carbondale, Illinois	2560	160	392
Near West Frankfort, Illinois	2427	150	355

Measurements of stage, output, rainfall, and (some) inflow taken. Not completely equipped with self-recording instruments. Annual blue-print records of each lake. W. D. Gerber, Engineer.

[Note: Self-recording instruments are used to measure rainfall and runoff on all of the foregoing plots, unless otherwise noted. L. K. Sherman.]

APPENDIX C--THE INFILTRATION-THEORY OF SURFACE-RUNOFF

The general features of this theory as developed by Robert E. Horton were outlined in a paper entitled "The role of infiltration in the hydrologic cycle (Trans. Amer. Geophys. Union, 14th annual meeting, pp. 446-460, 1933). The complete theory as related to surface-runoff, with applications both to the analysis and synthesis of the hydrograph, is given in Surface-runoff phenomena, by Robert E. Horton (Publication 101, Horton Hydrological Laboratory, Voorheesville, New York, February 1, 1935).

In describing this theory the term "rainfall" is used in the sense of "ground-rainfall," that is, rainfall which actually reaches the ground after interception by vegetation has taken its toll.

The soil-surface acts as a separator or sieve through which water can flow at a certain rate, depending on the soil-type and condition. This rate is called the "infiltration-capacity."

That part of the rain which falls at intensities exceeding the infiltration-capacity is designated "rainfall-excess." If, for example, the rain-intensity is 1 inch per hour and the infiltration-capacity is 1/3 inch per hour, then the rainfall-excess intensity is 2/3 inch per hour.

In this paper an attempt is made to follow quantitatively and in their natural order the events involving surface-runoff during and following a period of rainfall-excess.

Runoff from the ground-surface into streams cannot take place unless there is some depth of water accumulated on the ground-surface along the stream-margins. This depth may be so small as to be imperceptible to an ordinary observer and yet capable of conveying a large volume of water into the streams.

First, considering a period during a storm in which the rain-intensity exceeds the infiltration-capacity, in accordance with the storage equation

Inflow = (outflow + gain of storage)

the surface-runoff which has taken place at any given time will be precisely equal to the total rainfall-excess minus the amount of water still remaining on the ground-surface. This is described as "surface-detention."

Next, consider a rain rising more or less gradually to an intensity i exceeding the infiltration-capacity f, continuing at an intensity greater than f for a time t_e and then ending, either gradually or abruptly.

Until the rain-intensity becomes greater than f the rain is all absorbed by the soil. This initial rain may therefore be disregarded in relation to direct surface-runoff except as it may affect the infiltration-capacity f. If, as is usually the case, the soil-surface contains numerous small depressions, then no active surface-runoff occurs until rainfall-excess has lasted long enough to fill up the surface-depressions by surface-runoff from their tributary drainage-areas. The time required for this is called the "initial lag-interval." There will then be some depth δ_1 of surface-detention on the entire area. This is called the "initial detention." Surface-runoff to the stream will then begin to increase rapidly, approaching as a maximum limit an intensity (i - f) equal to the rainfall-excess rate if the rainfall-excess lasts long enough. For uniform rain-intensity the maximum direct surface-runoff rate occurs at the end of rainfall-excess

and the runoff-intensity increases as long as the duration of rainfall-excess increases. The maximum runoff-intensity is not produced, as is assumed in the so-called rational theory of storm-water runoff, by a rain-duration equal to the "concentration-interval."

For any given drainage-basin there is necessarily some definite relation between the rate at which surface-runoff enters the stream-channels and the depth of surface-detention along the channel-margins.

It is shown, both by actual examples and from theoretical considerations, that the relation of depth of surface-detention to rate of direct surface-runoff can--except at the beginning of surface-runoff--be expressed by a simple power function of the form

$$q = K\delta^M$$

where δ is the depth of surface-detention along the stream-margin and M is an exponent which is constant for a given drainage-basin. The equation of the profile of surface-detention from the watershed-line to the stream-margin is developed and it is shown that for steady-flow conditions the profile is parabolic for all types of overland flow, whether turbulent or laminar, and consequently there is a constant relation [M/(M + 1)] between the average depth of overland flow and the depth at the stream-margin. This makes it possible to express surface-runoff rate in terms of average depth or volume of surface-detention.

For a given area and storm, if the rainfall, infiltration-capacity, and runoff are known, from the storage-equation

Rainfall - infiltration = runoff + detention

a graph of the surface-detention depth can be determined, and from this and the known runoff-rates the law of relationship between depth of surface-detention and rate of surface-runoff can be determined.

This relation, once determined for a given drainage-basin, can be applied to the synthesis of the hydrograph or to the calculation of runoff rates where the rain-intensity and infiltration-capacity are the only other known factors. This is in brief an outline of the theory as applied to the determination of direct surface-runoff.

In applying this method to the synthesis of the hydrograph from rain-intensity data, two equations, namely, the storage-equation and the equation of detention-depth-runoff rate, must be solved simultaneously for each time-interval. The problem of determining the runoff rate and detention-depth at any given time during rain is practically identical with the familiar engineering problem of determining the depth and volume of outflow from a storage-reservoir during a flood when the inflow-rate, capacity of the reservoir, and stage-discharge relation for the reservoir-outlet are known.

A simple, practical method of solving this problem, both in cases of routing of floods through reservoirs and in case of determining surface-runoff, has been developed by Horton. This method is based on the fact that during any given time-increment, the increment of supply, or rainfall minus infiltration, equals the increment of surface-detention plus the increment of outflow. The method is too complicated for presentation here but is fully described in Publication 101 above referred to.

The runoff rate and runoff graph at an outlet or point on the stream-channel are not the same as the rate and graph of direct surface-runoff from the area upstream from the outlet, owing to the fact that the direct surface-runoff is modified by channel-storage, in much the same way that ground rainfall is modified by surface-detention in the conversion of rainfall into surface-runoff.

Just as in the case of surface-detention, so in the case of channel-storage, there is for a given area and storm a definite relation between the volume of accumulated storage at any given time and the channel outflow-rate. After direct surface-runoff ends, channel-runoff continues and, excluding ground-water flow, is supplied wholly from channel-storage.

Suppose that from any given time t until runoff ends, the total volume of channel-outflow is q. This will represent the amount of channel-storage remaining at the time t. A series of such quantities plotted in terms of the outflow-rates for the different times will serve to establish the relation between channel-outflow rate and volume of channel-storage.

Cases analyzed in the paper show that the relation between channel-storage and rate of channel-outflow can--except for small depths of storage--be expressed by a simple power function

$$q = K_c S_c^M$$

where M is a constant exponent for a given channel section, usually 1.5 to 3.0, and S_c is the volume of channel-storage. This equation closely resembles the equation of an ordinary stream cross-section rating curve but with the gage-height replaced by S_c.

If part of the flow shown by a graph of a stream-rise is derived from ground-water, it is necessary before proceeding with the analysis as above described to eliminate the ground-water flow. Following the general lines of a method developed in England by D. Halton Thomson for the interpretation of records of ground-water levels and flow, the author has developed a precise and definite method for separation of ground-water flow from surface-runoff.

(1) A normal depletion-curve or curve of rate of ground-water flow in terms of time elapsed is derived from a hydrograph.

(2) A simple classification of stream-rises is given, by means of which it is possible from a hydrograph, in conjunction with data of coincident and antecedent rainfall, to determine what, if any, effect the rain produced on ground-water flow.

(3) With this and the depletion-curve it is possible to determine the amount of rise of ground-water, if any, resulting from a given rain and to separate the observed runoff into its components--surface-runoff and ground-water flow. The Thomson-Horton method represents a distinct advance over the crude methods hitherto sometimes used in Europe and in the United States for this purpose.

After rainfall ends, infiltration continues for a time from surface-detention. The surface-detention becomes zero first at the watershed-line, then progressively approaching the stream, and is soon removed by the combined action of infiltration and surface-runoff. It is shown that the time at which direct surface-runoff ends corresponds approximately to the time of occurrence of a point of inflection on the recession-side of the channel runoff-graph. This fact may be used in fixing the part of the runoff graph which can be utilized in the derivation of a channel-storage and outflow-rate relation. The channel-storage and outflow-rate relation derived in the manner described from measured outflow-graphs can in turn be used for the construction of a channel-outflow graph where a channel-inflow or surface-runoff graph has been determined.

Owing to the rapid disappearance of surface-detention after rainfall ends, the duration of rise in a graph of surface-runoff from a given rain--especially if long-continued--is much greater than the duration of recession.

It is well known that in the case of channel-runoff, as distinguished from pure surface-runoff, the reverse is true, that is to say, the duration of the recession-side of a runoff-graph of a stream is greater (usually 1-1/2 to 3 times as great as the duration of the rising side of the graph). The graph of a stream-rise is therefore virtually turned end for end as a result of its travel, even for a short distance, in a stream-channel. This is the effect of the operation of channel-storage and results from the fact that after surface-runoff into the channel ends, the remaining channel-storage drains out more and more slowly as the volume of storage decreases.

Reverting to the detention-depth and runoff-rate relation, $q = K\delta^M$, it is shown that the exponent M depends on the type of overland flow and to some extent on the uniformity of depth of overland flow adjacent to the stream-margin. For uniform depth of marginal flow, M varies from 5/3 for turbulent, to 3.0 for purely laminar, flow. Indices are developed by which the degree of turbulence in the surface-runoff may be determined. Several cases are analyzed in the paper, from which it appears that, while overland or sheet-flow is usually mixed, that is, part turbulent, part laminar, yet turbulent flow predominates, especially near stream-margins, where the depth δ is greatest.

In general, the coefficient K has about the value which it would have for purely turbulent flow. The coefficient K is particularly interesting. It can be shown that for turbulent overland flow, the value of K is expressed by the equation

$$K = 449.5\sqrt{S}/n\,\ell_0$$

where surface-runoff rate is expressed in depth in inches per hour by the equation $q = K\delta^M$ and δ is marginal depth of surface-detention in inches.

The equation for K for turbulent flow includes three factors, depending on the physical characteristics of the drainage-basin: (1) Ground-surface slope, S; (2) surface roughness-coefficient, n; (3) length of flow, ℓ_0. The familiar "factor of imperviousness" and "inlet-time" of the so-called rational theory of storm-water runoff are here, in effect, replaced by infiltration-capacity and the coefficient K. Detailed discussion of the relation of the factors S, n, and f, and the initial detention δ_1, to runoff intensity and total runoff, is reserved for a subsequent part of the author's study of this subject.

Surface-runoff phenomena are governed completely and uniquely by:

(1) Rainfall-characteristics, including rain-intensity and duration and distribution in time, and also areal distribution over the drainage-basin.

(2) Infiltration-capacity and volume of depression-storage. A rule is given for determining the infiltration-capacity of a drainage-basin in a given storm from records of rainfall and runoff. This rule is: Infiltration-capacity equals the total rainfall from the beginning of rainfall-excess to the end of surface-runoff, minus the total surface-runoff, the difference being divided by the duration of rainfall-excess plus one-half of the remaining duration of surface-runoff after rainfall-excess ends.

The theory of surface-runoff based on infiltration and the application of the storage-equation provides a means of deriving directly from measured rainfall and runoff the fundamental factors which determine the runoff characteristics of a given area, namely, (1) infiltration-capacity, (2) detention-depth and surface-runoff relation or the law of overland flow and discharge, and (3) volume and stage-discharge relation for channel-storage. Given these factors they can be applied to the calculation of hydrographs from rainfall-data alone. Unfortunately details of the methods of calculation and application cannot be presented in abstract form.

It is suggested that analyses of hydrographs should be carried out by the methods described in numerous instances and the results published, thereby furnishing a series of experimental values of the quantities and relations which determine surface-runoff, so that these factors and quantities can be used as guides to the judgment in selecting appropriate factors for application to other areas.

APPENDIX D--REPORT OF ADVISORY COMMITTEE ON RAINFALL AND RUNOFF TO THE NATIONAL RESOURCES BOARD

The Advisory Committee of the American Geophysical Union, in reporting to the Mississippi Valley Committee and United States Geological Survey, commends the work in applied hydrology undertaken by the Mississippi Valley Committee and its staff. It realizes that the ultimate purpose of the work is for the better economic usage of the water resources of the Nation. In order that the conclusions may be sound it is essential that the underlying hydrologic data be correctly applied. It is this scientific phase of hydrology with which the Advisory Committee is concerned.

In this report the Committee discusses the investigations and studies, which have been presented by the staff of the Mississippi Valley Committee, together with recommendations as to future procedure. In this consideration the subject-matter will be divided as follows:

Topic A--Preliminary data: Runoff formulas
Topic B--Statistical methods: Flood-frequency
Topic 1--Study of long-time rainfall and runoff records
Topic 2--Analysis of monthly precipitation, temperature, and runoff records
Topic 3--Determination of ground-water stream-flow by hydrographs and depletion-curves
Topic 4--Analysis of precipitation and runoff during drought-periods
Topic 5--The unit-hydrograph applied to estimates of runoff from rainfall

Topic A--Preliminary data: Runoff formulas

The Committee has received several useful preliminary statements relating to the numerous types of empirical runoff-formulas and accompanied by bibliography. "Rainfall-runoff relations" by W. G. Hoyt is good presentation of the most important formulas and procedures. The Committee is of the opinion that in the work of the Mississippi Valley Committee:

(a) Empirical runoff-formulas of the older type, which do not contain the factor of rainfall, should be omitted.

(b) That several of the later peak runoff-formulas, including those of Pettis, Jarvis, Besson, and Grunsky, should be applied to a number of drainage-basins under comparable storm-conditions.
(c) That the results in tabular form should be published together with the results derived from the same basins by the use of the unit-hydrograph method and statistical frequency-methods.
(d) The foregoing should be accompanied by necessary notes where identical conditions cannot be applied.

Topic B--Statistical methods: Flood-frequency

Several important studies by the Mississippi Valley Committee staff have been received: "Methods for estimating floods" by H. Alden Foster (May 1934); "A study of methods of estimating flood-flows applied to the Tennessee River" by Thorndike Saville.

Mr. Grover (June 30, 1934) presented a comparison of results for 5-, 10-, 100-, and 1000-year frequencies based upon several different mathematical procedures. The figures were in quite close agreement. Mr. Grover concluded: "It is believed that the consideration of flow-events, as represented by the maximum daily flow of such flood-rise, is to be recommended for the present project." He asks for opinions as to the term "intensity"--whether ultimate severity or use of the term 100-year or 1000-year frequency.

Mr. Saville's paper gives a much-needed analysis and comparison of the application of the several statistical methods now in use. Foster discusses statistical methods and formulas of the flood-frequency type. In this class he includes the formulas of Fuller, Horton, Lane, Meyer, and Creager.

The American Geophysical Union Committee is of the opinion that a comparison of the aforesaid flood-frequency formulas applied to the same basins used by Saville in his work would be of value.

This Topic B is primarily within the special domain of the Advisory Committee on Flood Control, American Society of Civil Engineers. Members of the American Geophysical Union Committee, however, have presented comments on the subject as follows: Mr. Meyer feels that " a mere statistical analysis of recorded floods is an unsafe basis for any estimate of probable flood-magnitude and frequency unless the records extend over at least 25 years and that the causes of floods must be studied in the light of the hydrological data available." G. W. Pickels presented (June 25, 1934) some very pertinent observations on statistical methods. Among them are the following: "I agree that the basic flow above which flood-phenomena are to be considered should be the value of the smallest recorded annual maximum one-day flood." Also, "I do not believe that the length of flow-records warrants the inclusion of flow-estimates beyond the 100-year frequency, or the one per cent chance flood."

The American Geophysical Union Committee concurs with the specifications applicable to flood-frequency methods set forth by the Chairman (G. H. Matthes) of the Committee on Flood-Protection Data, American Society of Civil Engineers, in his letter of June 28, 1934.

The American Geophysical Union Committee recommends that, inasmuch as the staff of the Mississippi Valley Committee is engaged on a comprehensive compilation of flood-data which requires it to examine a large number of stream-flow records, it would be a comparatively simple matter for that staff to extract from these records, data pertaining to low-water conditions, which are of fundamental interest to any organization charged with the study of the water resources of the United States. Those compiling flood-datum could, with a small additional outlay of time, compile also a record of low-water flows.

Topic 1--Study of long-time rainfall and runoff records

The American Geophysical Union Committee has reviewed two studies of long-time rainfall and runoff records. One on the Mississippi Basin above Keokuk, Iowa, and the other on the Tennessee River above Chattanooga. W. G. Hoyt (August 28, 1934) is of the opinion that the studies disclose: "(a) Apparent changes during the period of record in the amount of annual runoff for a given precipitation, the relations showing a tendency for a somewhat smaller amount of annual runoff for a given precipitation during the latter part of the period of record; (b) noticeably different trends between annual precipitation and seasonal precipitation."

The relations worked out for these streams were extremely interesting, particularly indicating the tendency towards a constant value of the losses. This study and the study for the tribu-

taries bring out more clearly than ever that the runoff must be considered as a residue, and that there is a definite characteristic loss for each basin, the basin tending to take up a certain amount of moisture regardless of precipitation, but that this is affected somewhat by extremely low value of precipitation.

Mr. Meyer is inclined to agree with Mr. Hoyt's interpretations as in (a) and (b) above, but in general that the adequacy of the data is not sufficient to make the conclusions fully acceptable.

In view of the recent drought-situation in the central west, a similar study for, say, the Red River of the North or the Upper Platte River would be very useful in possibly showing trends. Such study might assist in solving the important mooted questions: Are the depleted ground-water and stream-flow condition man-made or is the normal supply of rainfall growing smaller? For this reason a study of long-time rainfall-runoff relations is valuable and should be continued.

Figures for "average annual" rain or stream-flow conceal the important element of variation in seasonal distribution. If it can be worked into seasonal phases, so much the better. Mr. Sherman (August 15, 1934) compiled, from the Mississippi data, an interesting tabulation showing a consistent variation in average infiltration-losses with average annual rainfall. Such analogy will not apply to short-time periods because the effect of antecedent rainfall or of drought becomes apparent.

Topic 2--Analysis of monthly precipitation, temperature, and runoff records

Analysis of this kind is valuable. They are basic to all formulas and procedures in estimating or forecasting surface-runoff or ground-water stream-flow from rainfall-data. They are basic because the coefficient of runoff (percentage of runoff) depends primarily upon the soil-moisture condition of the particular basin under consideration. Runoff is governed by infiltration and other losses--evaporation and transpiration. All three subtractions from rainfall may be considered together as losses. The amount of loss is affected by a number of variables. This number of variables may for practical purposes be reduced to three, namely:

(1) Amount of antecedent rainfall and its time-distribution (intervening dry days)--This factor affects soil-moisture conditions.
(2) Month or season of the year--This factor includes the effect of temperature, evaporation, and plant-demand (transpiration) which in turn affect soil-moisture conditions.
(3) Amount and intensity of concurrent rainfall or the rainfall under consideration.
(See also Topic 5)

The recent studies made by the staff of the Mississippi Valley Committee, by Adolph Meyer, by Mr. Lee's Committee of the American Geophysical Union on Infiltration-Losses, by Robert E. Horton, and many others indicate that a satisfactory, practical solution of this important problem--based upon the three aforesaid grouped factors--may be devised. This analysis should be continued by the staff of the Mississippi Valley Committee. A study of the fluctuations of ground-water from observations on wells may disclose useful facts when comparison is made with the allied meteorological history. Any attempt to improve our knowledge with reference to drought-conditions is worth while. Ground-water investigations from wells is probably of special value in situations where the water-table has fallen below the stream-beds. Where any stream-flow from ground-water exists, the correlation of such ground-water flow with the elevation of the water-table is reflected by the observed depletion-curve. In the latter situation the study of well-records is of lesser economic importance.

Topic 3--Determination of ground-water stream-flow by hydrographs and depletion-curves

Attention is directed to the paper of Iwasaki (J. Amer. Water Works Ass., February 1934) as a good illustration of the application of the depletion-curve to the forecasting of ground-water stream-flow. The method is not new. The Committee is of the opinion that the depletion-curve method offers the most definite and logical procedure now available for estimating ground-water stream-flow.

(a) The American Geophysical Union Committee is of the opinion that a study of basin-characteristics with hydrologic features will eventually produce results of very practical value. The Chairman advises as follows: "I have been much impressed by the studies coming under this head, and will answer to Item A in the affirmative. As to B, however, I should not have placed latitude and altitude as primary factors, as these would seem to be only incidental and would largely come in under temperature. In this connection, I have been impressed in the past by our

failure to utilize information developed in other related fields of science. Would it not be possible to analyze the hydrographs by the Bernard method both as to flood-flow and sustained flow, and from these attempt to correlate basic characteristics, bringing in at this point the analyzing of the Bernard factors in studies by geologists and soil physicists (particularly studies growing out of agricultural engineering). It would seem that the observations in connection with soil-erosion might shed some light on such a correlation." The basin-characteristic expressed (as Mr. Bernard has done) in a single factor "U", seems to offer a useful instrument in hydrologic research. The unexplored field, however, is now so great that the American Geophysical Union Committee questions the advisability of the Mississippi Valley Committee's attempting more than the exploratory study now under way within the scope of the present authorized period.

(b) We understand that new isohyetal and isofluvial maps of the United States are now being prepared by the staff of the Mississippi Valley Committee. Such maps are a useful guide in the general comparison of hydrological conditions in different sections of the country. They are based upon long-time annual averages. They are subject to wide seasonal or annual departures. They are of minor value in reference to economic application such as water-supply, agriculture, or water-power. The novice should be warned that the unconsidered use of such maps will be misleading.

Topic 4--Analysis of precipitation and runoff during drought-periods

The American Geophysical Union Advisory Committee has received the following: "The water-table of the Mississippi Valley." This is a discussion of the general subject, accompanied by bibliography. "Relation of rainfall and runoff during drought-periods" on selected streams--Mississippi Valley Basin. The tables and diagrams showing rainfall relation above Keokuk (July 9, 1934) are important in this connection.

This matter is in a sense a special case of the three preceding topics. Mr. Horner is not greatly impressed with the possibilities of separate studies during drought-periods. Mr. Sherman is of the opinion that certain work in this field may be of value as indicated in Topic 3. Mr. Meyer has discussed the matter indirectly in connection with his tentative conclusion that the long-time records indicate a definite lowering of water-table and a progressive reduction in ratio of runoff, and is apparently inclined to treat the drought-period as distinct from the general study. Hoyt, in his memorandum of August 28, 1934, indicates that the matter should be tied up to ground-water levels at a large number of wells, and as something of this kind is to be undertaken, the final conclusion under this topic might be held in abeyance. Except for this possibility, no further studies of the type referred to would seem to be justified.

Topic 5--The unit-hydrograph

Under date of August 20, 1934, the American Geophysical Union Committee received "A preliminary manual for the unit-hydrograph method of determining stream-flow" by Merrill Bernard. This manual treats the subject in a comprehensive manner and discusses in detail several allied special features. These special features must not be confused as being a basic part of the unit-hydrograph method, valuable in themselves as they may be. This refers in the manual to items 4 and 5 "Storm-flow coefficients"; page 7, "Limiting flood-hydrographs," the "Pluviograph," and the drainage-area characteristic factor. The American Geophysical Union Committee appreciates that a more elementary statement is desirable and that some form of a primer will be prepared with Mr. Bernard's assistance. It is suggested that the inventory outlined below by Mr. Sherman be taken as a basis for such primer and that this primer should not attempt to cover matters contained in the manual, such as "storm-coefficient" and "depletion-curve," that were not a part of the original unit-hydrograph theorem.

L. K. Sherman offers the following comments on elementary principles and limitations applying to the unit-hydrograph method. Since the appearance of Sherman's paper on the "Unit-graph" (Engineering News, April 7, 1932), a number of important discussions have been made. These include a thesis by Cecil Boling (Massachusetts Institute of Technology), a thesis by Mr. Smart (Ohio State University), and especially the paper by Merrill Bernard (Proc. Amer. Soc. Civil Eng., January 1934). All of these indicate that it is now time to take an inventory, to point out limitations of application, limitations of accuracy, and to restate the principles in improved terms.

Basic hypothesis of the unit-hydrograph method--(1) The unit-hydrograph method is a procedure for determining the peak or other rates of runoff from a particular basin, by analogy, from an observed rainfall and the corresponding observed hydrograph of runoff from the same given basin.

(2) The hypothesis upon which the unit-hydrograph method is based is as stated in Bernard's manual, namely: "In a given drainage-basin runoff from rainfall occurring in a unit of time will produce hydrographs of equal bases and the ordinates will vary with the intensity of the net rainfall." (Net rainfall meaning rainfall minus infiltration and other losses.)

(3) Distribution-graph--The first step in the application of the method is to find a hydrograph of runoff for the given basin due to an isolated one day (or unit-time) rainfall. (This is found by inspection of the United States Weather Bureau records of daily precipitation and the United States Geological Survey records of stream-flow due to said rainfall.) Bernard's "Distribution-graph" and Sherman's "Unit-graph" effect the same purpose. The distribution-graph term is simpler and preferable.

The average daily rates of observed flow for the runoff period due to the one day of rain are given in the United States Geological Survey Water Supply paper for the basin. These daily rates of stream-flow include both surface-runoff and base or ground-water flow. Estimate this base-flow. Subtract this base-flow from each of the observed flows. Also deduct antecedent flow, if any. This will give the segregated flow or surface-runoff due wholly to the rainfall in question. Find the percentage that each day of segregated flow bears to the total segregated flow. These figures will total 100 per cent. They form the distribution-graph.

(4) Application--To find the hydrograph of runoff due to any given 24-hour depth of rainfall, proceed as follows: First multiply the given 24-hour rainfall depth by the coefficient (or percentage) of runoff. This will give the depth "d" on the area in question. Multiply "d" by 26.89 M, where M = drainage-area in square miles. This gives the total runoff expressed in cubic feet per second for a 24-hour period. The aforesaid runoff-figure, multiplied in turn by each daily percentage of the distribution-graph, will give the ordinates n_1, n_2, n_3, etc., for the average rate of runoff (in cubic feet per second) per each 24-hour interval of the runoff period. They form the required hydrograph of runoff.

(5) Application for several or successive rainfalls--When a second rain follows at the end of the first day--or x days after the first day--compute the figures for the ordinates n_1, n_2, n_3, etc., in exactly the same manner as given above. When the second rain follows at the end of the first day, then the runoff n_1' due to the second rain flows in the stream with the antecedent day's runoff n_2. The stream-flow on the second day in this case is thus $(n_2 + n_1')$. Similarly on the third day the stream-flow is $(n_3 + n_2')$, etc. If the second day has no rainfall but rain occurs on the day, then the overlapping hydrograph begins at the end of the second day. The combined hydrograph is then found by the addition of the stream-flow as follows:

			Day			
1	2	3	4	5	6	7
Rain		Rain				
n_1	n_2	n_3	n_4	n_5		
		n_1'	n_2'	n_3'	n_4'	n_5'

A convenient form for summation or building up overlapping unit-hydrographs into the single or combined hydrograph was devised by Sherman (Eng. News-Record, April 7, 1932).

Examples of summation are given by Bernard (Proc. Amer. Soc. Civil Eng., January 1934) and Bernard's manual on bottom of Plate 1. Bernard applies his "storm-coefficient" after the summation for 100 per cent runoff or "pluviograph."

[Note--The foregoing paragraphs 1 to 5 cover all the essential features of the unit-hydrograph method.]

Comments

Base-flow is stream-flow from ground-water (sometimes called dry-weather flow, ground-water flow, depletion-flow, or--erroneously--"normal" flow). The unit-hydrograph deals only with surface-runoff. Therefore, base-flow must be deducted in deriving a distribution-graph. In computing stream-flow from rainfall by the unit-hydrograph method the base-flow must be estimated and added to the computed rates of runoff. Estimates for base-flow may be made by several methods. Sherman (Eng. News-Record, April 7, 1932) used the simple but roughly approximate method of Meinzer and Houk. The depletion-curve method described by Horton and others is more accurate. A good illustration of the depletion-curve is given by Iwasaki (J. Amer. Water Works Ass., February 1934).

Coefficient of runoff, percentage of runoff, or storm-coefficient is a factor to be applied to rainfall which will affect the runoff or net rainfall. This factor is the most important element in all formulas or methods (including the unit-hydrograph) used in computing runoff from rainfall. The unit-hydrograph prescribes no special method or process for deriving or applying the runoff coefficient--that is left to the individual engineer or hydrologist. The subject-matter covers a large chapter of hydrology and much remains to be done. Material advancements have been made in recent years by Lee, Horton, and others.

Bernard's method of applying the "storm-coefficient" has been mentioned. While this method may not be hydrologically correct, its use for a particular basin might develop a first approach to a coefficient of runoff that would be applicable to the basic conditions surrounding the rain being studied, and might be a guide to the development of a series of coefficients of runoff that would be applicable throughout the range of seasons and conditions.

Smart derived curves from observed data for the average percentage of runoff for each of the four seasons or for a two-month period, as related to intensity of 24-hour rainfall. He adhered to the single graphs without interpolation. If the given rainfall furnished the average percentage of runoff, the computed results check with observed flow. If the runoff was 100 per cent above or below the average percentage, his results were 100 per cent in error. Sherman used a diagram based upon the relation of percentage of runoff for a given month to the equivalent 24-hour rainfall plus an empirical amount based on antecedent rainfall and its distribution, the idea being to take cognizance of soil-moisture conditions. Sherman groups the effects of losses to rainfall, so far as surface-runoff is concerned, into three principal factors: (1) Antecedent rainfall, amount and distribution; (2) the month or season of the year--this affects evaporation and transportation; and (3) the amount and intensity of the rainfall in question.

The best procedure for forecasting quantitatively the amount of rainfall-loss to runoff, the coefficient of runoff, or the "storm-coefficient" has not yet been fully devised. The solution cannot be made in any intensive procedure of research. Any contributions which the staff of the Mississippi Valley Committee may discover relative to quantitative rainfall-losses will be of value. The American Geophysical Union Committee does not deem that it is now wise or practicable for the Mississippi Valley Committee to attempt to furnish the best method for determining the coefficient of runoff, but the work on the Bernard "storm-coefficient" might be carried forward to some extent to determine its possible ultimate value.

Drainage-basin characteristics--Mr. Bernard has apparently developed the possibility of a single factor reflecting the physical characteristics of a drainage-basin. It has attractive possibilities in that it might serve to apply the unit-hydrograph method to basins which do not have any guiding runoff-data. The test will take much time and research. The American Geophysical Union Committee is of the opinion that this work should not be attempted by the Mississippi Valley Committee unless a further extensive research project is authorized.

Limitations of the unit-hydrograph for winter conditions--The unit-hydrograph method is not generally applicable when the basin or stream is covered with snow or ice.

Size of basin--The unit-hydrograph method can be applied to any basin over two or three square miles in area and up to ten thousand or more square miles. A shorter unit of time than 24 hours is required for flat areas under approximately 500 square miles or for hilly areas under approximately 1000 square miles.

Arid districts--The unit-hydrograph method applies only to surface-runoff. Obviously it cannot be used when infiltration or loss equals the rainfall-rate.

Stream-gagings--The unit-hydrograph is not a substitute for stream-gagings or records. At least some such data are essential before the required distribution-graph can be obtained. Graphs from net rainfall exceeding one inch are preferable.

Accuracy of results

(1) The hypothesis of the unit-hydrograph method has been substantiated within certain practical limits by the following:

(1) Agreement of distribution-graphs derived on basins under widely varying rates of rainfall and infiltration by Sherman, Bernard, and others.
(2) Test by application to recorded stream-flow records.
(3) Studies by the Committee on Floods, Boston Society of Civil Engineers.

(4) Comparative analysis by L. K. Sherman in a paper "Hydraulics of surface-runoff and stream-flow," on file in Engineering Societies Library, New York, and in library of the American Geophysical Union, Washington, D. C. This paper brought out the following facts:

(a) The hypothesis of direct proportion of ordinates in the unit-hydrograph is not accurate for small areas involving only a few acres. The relation rapidly improves in accuracy as the area increases to two square miles or more. This is due to the "ironing-out" process with the element of time.

(b) Comparison between computed hydrographs and observed stream-flow hydrographs frequently lacks exact synchronization. This is due to difference in time of transit based on the velocity for the observed distribution-graph and time of transit at much lower stages. It may be rectified if conditions warrant the labor.

(c) Distribution of rainfall--Inequality of rainfall-distribution over the basin does not materially affect the accuracy of results excepting under extreme conditions. With a very heavy rain at only the lower end of the basin, the computed runoff will be too low. With a heavy rain at only the upper end, the computed runoff will be too high.

(2) The coefficient of runoff--Accuracy of results by the unit-hydrograph method depends largely upon the ability of the engineer or hydrologist to determine the proper infiltration-loss or coefficient of runoff. Until improved quantitative or mechanical procedures are established it is important that one who applies the simple unit-hydrograph method (or any rainfall-method) be familiar with the basic factors affecting infiltration and runoff. This statement applies more particularly to ordinary conditions of rainfall. For flood-rainfall it may be possible to select the runoff coefficient within relatively small limits of error.

Application

The unit-hydrograph is a useful method for the analysis and estimate of surface-runoff from rainfall. It is particularly applicable for estimating flood-conditions probable but not yet observed. The method is not confined to any assumptions as to uniform rates of rain or to a concentration-period. All sorts of possible hypothetical storm-conditions may be compared. The unit-hydrograph, in the form of the distribution-graph, is a true index of the basin-characteristics affecting peak-rates of runoff.

Recommendations

The American Geophysical Union Committee recommends that the Mississippi Valley Committee through its staff (1) derive and publish a set of distribution-graphs for several typical basins throughout the country, (2) derive and publish flood-hydrographs computed from possible hypothetical storms of a known rainfall-frequency upon the several basins, (3) make a tabular comparison of such derived peak-rates of flood-flow with the several other methods, such as the statistical-methods and certain of the rainfall-runoff formulas.

[Note: The above recommendations have been prepared by the Advisory Committee of the American Geophysical Union, having the following personnel: W. W. Horner, Chairman; L. K. Sherman; A. F. Meyer; G. W. Pickels; Roy Towl; and J. W. Woerman. The recommendations have been prepared primarily by Messrs. Sherman and Horner, with the assistance of Mr. Meyer as to a certain portion, and with criticism from other members of the Committee. All members of the Committee are not necessarily committed to all details of the recommendations.]

APPENDIX E--RELATION BETWEEN RAINFALL, RUNOFF, AND WATER-LOSSES IN SWEDEN

Bulletin 20 of the International Association of Scientific Hydrology of the International Union of Geodesy and Geophysics, published in 1935, contains an important paper (pp. 129-137) by Axel Wallén giving maps, tables, and diagrams showing the average rainfall, runoff, and water-losses on 24 drainage-basins in Sweden, all with records of ten years or more.

Wallén has worked out the coefficients of correlation between rainfall and runoff for these basins and obtains the general formula

$$Y = 1.03\ P - 375$$

where Y is the runoff and P is the mean rainfall, both in millimeters per year.

Designating average water-losses by L,

$$L = P - Y = 375 - 0.03\ P$$

The coefficient of correlation between the mean rainfall and mean runoff of these basins is 0.98. This, of course, can be true only where, as the formula above given shows, the water-losses are almost constant.

It is interesting to note that the same publication contains papers by Collins and Snyder, by R. E. Horton, and by H. K. Barrows, showing, for different drainage-basins in eastern United States, only a moderately high degree of correlation between rainfall and runoff. The difference between the conditions in the United States and those in Sweden illustrates the danger of making too broad generalizations in matters of hydrology.

The reason for the almost perfect correlation between rainfall and runoff in Sweden is due, no doubt, in part to the uniformity of climatic conditions, but it is also due in a large degree, as Wallén states, to the fact that "these drainage-basins contain a great number of lakes, swamps, and forests but not much open ground, cultivated fields, or grass-land, so that the basins have a rather high power of retention of waters falling thereon." Apparently there is little or no direct surface-runoff.

Variation in direct surface-runoff is the principal cause of variation in the relation between rainfall and runoff. Horton has shown that there is a high correlation between total infiltration and water-losses even in basins where there was only a moderate correlation between total runoff and water-losses. The water-area in the various drainage-basins included in Wallén's study ranges from 1 to 16 per cent and there is a considerable variation in the relation between rainfall and runoff for individual drainage-basins.

Wallén has worked out the coefficients of correlation between rainfall and runoff for the individual basins and these range from 0.92 to 0.99.

He has also given the equations of linear regression for the individual basins and it is of particular interest to note that for about half of the basins--those having generally the smaller rainfall--the water-losses increase slightly with increase of rainfall, while for the other half of the basins--those with generally heavier rainfall--the water-losses decrease slightly with increase of rainfall. This again shows the reason for the remarkably high coefficient of correlation between mean rainfall and mean runoff in this region. Owing to the large water-surface in lakes and swamps and the climatic conditions, the average rainfall for the whole region is very close to that corresponding to maximum water-losses. Where the mean rainfall on a drainage-basin is less than the average, the water-losses generally increase with increased rainfall; if the mean rainfall is greater than the average, the water-losses generally decrease with increased rainfall. Since the slope of the water-loss line on a graph of relation between rainfall and water-losses is obviously zero at a maximum point, variation in rainfall from the mean produces only slight variation in water-losses, and accounts for the nearly perfect correlation between rainfall and total runoff.

Wallén's paper is crowded with excellent data, well presented. The data he used have been corrected for gain or loss of surface-storage in lakes and an approximate correction has been made for gain or loss of ground-water storage by taking the rainfall for a water-year beginning and ending one month earlier than the runoff-year.

REPORT OF THE COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1934-35

F. J. Veihmeyer, Chairman

The Committee has endeavored to secure information concerning the total pore-space of soils in place in the field. A questionnaire was sent to at least one investigator in every state and in many cases to several. It was hoped to get an expression of opinion and data from competent investigators in diverse fields and different localities. The following questions were asked:

(1) Do you find the knowledge of the total pore-space in soils in place in the field useful in your work? If so, in what manner?
(2) Have you made measurements of the total pore-space of soils in place in the field? Are your measurements available? What method was used in making the determinations? A summary of your measurements or references to your publications will be appreciated.
(3) Have you found consistent differences between the total pore-space of coarse- and fine-textured soils in place in the field of the same soil-series, or have you an opinion on this question?

A gratifying response was received. A fairly large number who answered the inquiry had no information or opinion to offer. Many others had opinions based on a priori reasoning but had no data. A relatively few had data concerning the porosity of soils of the same series. Because it is obvious that the differences in porosity might occur in soils of different origin, it was thought desirable to limit the discussion to soils of the same series. Furthermore, only porosity-measurements of soils in place in the field were to be considered. Almost without exception, the replies indicated that knowledge of total pore-space was valuable from many viewpoints.

While of no great importance from a theoretical consideration, a knowledge of the total pore-space of field-soils is valuable in engineering and related fields. The Committee, of course, is aware of the fact that resistance to flow of water in soils and many other physical properties are influenced more by the size and possibly the arrangement of pores than by the total pore-space, a point to which many of the contributors called attention. Since it was decided to consider total pore-space alone, no attempt was made to include a discussion of the latter point. The statement is frequently made that porosity increases with fineness of soil-texture. Sometimes this idea is used in the design of drainage-systems.

In the following presentation the terms volume-weight and apparent specific gravity are used interchangeably and mean the ratios of weights per unit-volume of dry soil to water.

Most of the porosities were calculated from the volume-weight from an assumed specific gravity of soil-grains of 2.65. In some instances, however, the specific gravities were determined for each sample.

Space does not permit listing all the replies and comments received and the statements used have been materially condensed. The assistance of N. E. Edlefsen of the Committee in preparing the abstracts for the report is gratefully acknowledged.

F. J. Alway (University of Minnesota) refers to the measurements of pore-space made by Neal [see references 12 and 13 under section "Literature cited"] and, while not having made comparisons between coarse- and fine-textured soils for the same series, expects the pore-space to increase in general with the increase in the fineness in texture.

L. D. Baver (University of Missouri) thinks that the total pore-space is one of the important factors in relation to permeability of clay-pan soils. He obtains the undisturbed samples from the field by means of a special soil-core sampler [14]. He finds no large differences in the total pore-space between different textured soils except as influenced by organic matter.

S. H. Beckett (University of California) has made a comparison of the apparent specific gravity as determined by the soil tube [19] and viscous liquid methods [1]. Results with the two methods agree fairly well. The average results for four soil-types were: Kimball sandy loam 6.1, 1.85; Sierra sandy loam 6.1, 1.63; clay-loam subsoil 18.2, 1.74; and Yolo fine sandy loam 20.0, 1.37 for the moisture-equivalent and volume-weights, respectively. He also presents data on various types of soil for each foot-section to a depth of six feet from which he draws the conclusion that the general tendency seems to be toward a decrease in pore-space in the lower depths.

H. F. Blaney and C. A. Taylor (United States Department of Agriculture, Bureau of Agricultural Engineering) refer to published results [2] of volume-weight measurements on soils in northern San Diego County, California, ranging from a Sierra sandy loam with moisture-equivalent of 10.5 and volume weight 1.43 to Aiken loam with moisture-equivalent of 18.0 and volume-weight of 1.56. The soil with lowest volume-weight, 1.36, had a moisture-equivalent of 13.0. They used the soil-tube method of making volume-weight measurements, but found good agreement between the soil-tube [19] and viscous liquid methods [1]. Additional measurements were supplied by them on soils in Ventura County, California, in connection with their studies on rainfall-penetration [3].

The moisture-equivalents are not given but the soil-type is designated. The smallest volume-weight was that of a Yolo silt-loam, 1.14; the highest, 1.84, was Ojai very fine sandy loam. A Yolo gravelly fine sandy loam had a volume-weight of 1.35. Several Yolo silt-loams in different localities were tested and were found to have higher volume-weights than some of the sandier soils in this series. Blaney and Taylor took samples to a depth of 17 feet in 1-foot sections which show noticeable change in texture of soil. In most instances, the volume-weight varied with texture but samples were not sufficient to determine whether there is a consistent difference.

G. D. Bodman and N. E. Edlefsen (University of California) from studies on Yolo soils at Davis have found that total pore-space of field-soils is one of the factors, although not in all cases the most important one, influencing the rate of downward movement of water. Bodman has made determinations of volume-weights by use of tubes of various sizes and by the paraffin-immersion method [15]. He has investigated the relation of texture as measured by the moisture-equivalent and the pore-space of samples after being centrifuged for moisture-equivalent and found a correlation of 0.880 $\pm$ 0.002 between these two variables. Veihmeyer [21] also reports that volume-weight of centrifuged blocks of soil decreases as the moisture-equivalent increases.

O. C. Bruce (University of Maryland) while believing that a knowledge of the total pore-space would be an indication of the behavior of soils under a given set of conditions, thinks available methods of determining pore-space of soils in place in the field are inaccurate. For this reason he has not made measurements but he and his associates believe that the pore-space of coarse- and fine-textured soils within the same series do vary on account of differences in organic and colloidal material. The fact that differences in pore-space between different series and different textures do exist leads Bruce to think it is not reasonable to suppose that there would be no variations between the coarse- and fine-textured soils within the same series.

A. S. Curry (New Mexico College of Agriculture and Mechanic Arts) has reported [4] volume-weight of some soils in the Mesilla Valley, New Mexico, which are extremely variable as to texture and structure. Sands and clays with several intervening classes may occur in a depth of only a few inches which makes field-determinations difficult. He has been unable to make satisfactory tests because of the variation in the results obtained with the different methods tried. He used a cylinder 3.61 inches in diameter, the rubber-tube method [10], the viscous-fluid method [1], the soil-tube [19], and a revised sand-method [8].

I. A. Denison (United States Department of Commerce, National Bureau of Standards) refers to his and R. B. Hobbs' studies [5] in which the volume-weights of 34 soils ranging in texture from Norfolk sand with a moisture-equivalent of 2.3, and volume-weight of 1.55, to a Houston black clay with moisture-equivalent of 50.5, and volume-weight of 2.08. Volume-weight determinations were made on lumps shipped to the laboratory with precautions to preserve the natural structure and moisture-content of the soils as they existed in the field. The volume-weights of the lumps were determined by immersing them in a dish of mercury, calculating the volume from the weight of mercury displaced. Specific gravities of the soil-grains are not given. When the volume-weights of the 34 soils were plotted against their moisture-equivalents there appears to be a definite trend toward lower volume-weights for the coarser textured soils, indicating that the sands had higher porosities than the clays. Denison says that data on the total pore-space of the soils at sites where tests of corrosion of metals have been made enables him to account for the distribution of corrosion on the test-specimens and for the fact that, all other conditions being the same, pitting is so much more severe in certain soils than in others.

In his work the moisture-content of the soil is taken into account. The volume of voids is reported, which means the total spaces occupied by air in a mass of soil compacted by a definite force and having a definite moisture-content, the moisture-equivalent. Denison stresses the fact that the rate of movement of air in soils is controlled largely by the total space through which air may diffuse and, therefore, a comparison of the relative volumes occupied by air under specified conditions in the different soils might provide an index to their permeability.

N. E. Edlefsen (University of California) and Veihmeyer believe that so many factors may affect porosity of soils no one, such as particle-size, will be the controlling one, except in special cases where the influences of other factors remain fairly constant. Therefore, until the effect of each factor is quantitatively determined, porosity must be measured for each soil under consideration.

H. J. Fraser (International Nickel Company) gives a brief summary of measurements of the porosity of sands in situ, a full account of which will appear later [7]. He points out that local porosity in sand is appreciably higher in the immediate vicinity of a large pebble or boulder as a result of the effect of disturbed packing caused by the presence of the pebble or of differences in packing produced by variations in the methods of depositions caused by the presence of the pebble. His average porosity of pebble-free sand determined according to a method described in the American Journal of Science (v. 22, 1931) is 41 per cent. Samples for porosity-measurements of Revere Beach sand (Boston) adjacent to boulders gave the following results: Near surface 42.10; 3 inches below surface 42.66; and immediately underneath boulder 43.43 per cent. Three samples of well-rounded and well-sized sand with an average diameter of 1 mm from Revere Beach gave porosities of 39.25, 39.24, and 39.42 per cent. These porosities are about the same as have been reported for some fine-textured agricultural soils. Fraser points out that, while the actual size of unit has no influence on the porosity of uniform spheres pro-

viding they are considered as being contained in a container of infinite size, actually in materials of variable grain-size, the pebbles or large units have interstices that act as containers for the small grains and consequently this container effect becomes important. Grain-size also becomes important in the amount of compaction occurring during deposition because of variations in the mass; total surface-area ratio as the grain-size decreases, friction, adhesion, and bridging become of increasing importance because of the higher rates of surface-area to volume and mass, and consequently, the smaller grain-size the greater the porosity. Fraser gives this as his experience with materials of different grain-size in the laboratory and points out references to others who have found the same [6, 17, 18].

W. Gardner (Utah State Agricultural College), in common with many others who replied to the questionnaire sent out by the Committee, comments on the fact that the physical properties of soils are more intimately associated with size of the pores than with the aggregate pore-space. He believes that, while the total pore-space serves to measure the available space for water, it would be an easy matter to overestimate the importance of this characteristic.

S. S. Green (Department of Water and Power, Los Angeles) has made use of the pore-space in soils in his investigation of material for use in rolled earth-fill dams. He says the moisture-content of the soil determines, for a given method of rolling, the density that can be given to a soil in the embankment. The pore-space of the soil limits the amount of pre-wetting which can be done to the soil in place in the borrow-pit. He states that fine-textured soils in general have a greater pore-space, within a given soil-class, than have coarser textured soils. But he says that data show that this rule cannot be extended to soils of different series due to the spread in grading, which may be present in soils having a high clay-content.

A. F. Gustafson (Cornell University) says that a knowledge of total pore-space in soils is useful in connection with soil-erosion control in calculating the quantity of water a soil may take up before runoff begins. He has made determinations of volume-weight by use of a 3-inch tube from which pore-space has been calculated. He presents data on compact soils varying from a sand having a pore-space of 39.7 per cent to a clay with a pore-space of 58.2 per cent. He also gives data on some graded sands in which he found material passing a sieve 20 meshes to the inch, but retained on a 40-mesh sieve to have a pore-space when compacted of 36.83 per cent, whereas the material passing a 100-mesh sieve had a pore-space when compact of 40.49 per cent. He points out that if small particles are mixed with larger ones, the former may occupy the spaces between the latter, thus reducing the total pore-spaces, and thinks that this undoubtedly occurs in the field as soils become compacted.

H. J. Harper (Oklahoma Agricultural and Mechanical College) is working upon a method which can be used to determine variation in pore-space of undisturbed material. He thinks the variation in pore-space between plastic clay and sandy loam is significant but probably not as great as was expected. He gives an example of a Kirkland clay-subsoil with a pore-space of 49.1 per cent as compared with a Vernon sandy loam-subsoil which has a pore-space of 45.6 per cent. He is especially interested in the variation of pore-space in different soil-profiles and also in different parts of the same profile.

J. Kittredge (University of California) has some 200 volumetric samples from the San Gabriel Mountains of California taken with a two-inch tube but has not computed volume-weights or porosities. He says that he does not have an adequate basis for an opinion but thinks that a difference does exist in pore-space between coarse- and fine-textured mineral soils in place, under uniform conditions. He believes that the inconsistencies which have been noted are due to lack of uniformity in content of organic matter and in macrostructure.

C. H. Lee (Consulting Engineer, San Francisco) makes use of total pore-space measurements in his work on water-yield from underground basins, drainage, permeability, and flow of water through earth-structures, foundations, compaction of rolled-fill dams, shrinkage of fine-textured soils, and bulking and settlement of excavation and fill materials.

He has made no specific study of porosity of coarse- and fine-textured soils of the same series but believes that there might be some difference. This belief is based on the fact that porosity of earth-materials in the absence of substantial amounts of clay depends principally upon the diversity of sizes of particles and may vary from 17 per cent to 45 per cent or more. In clay or clayey materials, porosity depends very largely upon the degree of consolidation, and may vary from 35 per cent or 40 per cent up to a maximum of 85 or 90 per cent, the latter sometimes occurring in case of flocculated sedimentation from muddy fresh-water streams discharging in salt water.

R. S. Lewis (United States Department of Agriculture, Bureau of Agricultural Engineering) believes that a knowledge of the total pore-space is important in infiltration-studies. He feels that volume-weight measurements on field-soils are reasonably accurate bases for calculating porosities.

H. A. Lunt (Connecticut Agricultural Experiment Station) finds the knowledge of pore-space to be useful in his forest soil-research principally as it affects density of the soil and its water-capacity. He has made no comparative measurements but is of the opinion that fine-textured soils would have more pore-space than coarse-textured ones in the same series.

O. E. Meinzer (United States Geological Survey) is interested in the total pore-space of water-bearing material although he has not investigated soils. He states that the quantity of water that can be obtained from a water-bearing formation is determined approximately from the total pore-space and the moisture-equivalent. Total pore-space under field-conditions is one of the routine tests [16, 22] made on all water-bearing material in the Hydrologic Laboratory of the United States Geological Survey. If possible, samples are collected volumetrically in the field. If this can not be done, the apparent specific gravity is determined in the laboratory by compacting the samples as much as practicable. He concludes that there is no apparent consistent difference between the total pore-space of coarse- and fine-textured water-bearing materials. He thinks, however, that the results secured do not warrant a conclusive opinion on this question.

H. E. Middleton (United States Department of Agriculture, Bureau of Chemistry and Soils) has made some measurements on total pore-space [11] but thinks that the data do not warrant conclusions as to whether there is any consistent variation in pore-space with texture. He found that where the texture of adjacent horizons was similar there was little difference in pore-space, but where the change in texture was large the difference was also large.

J. H. Neal (University of Minnesota) refers to published results [12,13] of his measurements of the porosities of some Minnesota soils in which the actual pore-space was determined from the volume of water held in a block of the soil when all the pores were filled, being the same as the percentage of water in a saturated soil expressed on a volume-basis. The blocks of soil were secured from the field by driving a square iron-box into the soil to enclose a 6-inch cube. After carefully trimming the soil even with the edges of the box, the top and bottom were bolted on to prevent water from being drained out of the box. The amount of water necessary to saturate the soil and the dry weight of soil were subsequently determined. In the mineral soils tested by Neal, the pore-space shows a fairly uniform increase as the moisture-equivalent increases and there is a definite and close relationship between the two variables. Neal says that a knowledge of the total pore-space alone is of little use, but the amount of capillary and non-capillary pore-space should be known. His term non-capillary pore-space is similar to Denison's "volume of voids." Neal says: "The amount of non-capillary pore-space is an index to the rate of drainage of a soil in the humid regions. Since there is a relationship between pore-space and moisture-equivalent, the latter can be used as the index to measure the rate of drainage, as the moisture-equivalent is easier to determine than the pore-space."

M. L. Nichols (Alabama Polytechnic Institute) believes that there is a considerable variation in pore-space not only between different soils but in the same soil at different times and that the manipulation of soil in tillage-operations may be conceived to be largely dealing with variations in pore-space.

L. B. Olmstead (United States Department of Agriculture, Bureau of Chemistry and Soils) says that a minimum total pore-space might occur in a rather sandy soil that had a certain favorable particle-size distribution and that of any two soils of similar texture one might have a more favorable particle-size distribution or even particle-shape than another. Of two clay-soils it is possible that the one having strongly cemented aggregates, such as laterites, would have the smaller total pore-space. Subject to these qualifications, he thinks that of two nearby field soils of the same series, a comparison of corresponding layers at the same depth should show that the finer textured soil has the greater total pore-space. He bases this opinion in part upon the assumption that pore-space is determined upon dry soil with unswollen gel-colloid and in part upon the belief that sands more easily arrange themselves into close packing than do the clays. He also points out that determinations of specific gravity of soil-particles by the pycnometer-method using water probably gives too high a value due to compression of water near the solid liquid interface.

A. M. Piper (United States Geological Survey) believes a knowledge of the total pore-space of granular materials in place in the field is of paramount importance in ground-water investi-

gations, since it measures the capacity of the material to store water in the zone of saturation. He has made an extensive study of the porosities of soils in one of the best-known soil-series in California and has summarized the data for 14 localities. Samples of the soil in place were taken with a 6-inch diameter tube in one locality and with a soil-sampling tube [19] at the other places. The sampling was in one-foot increments to a depth of 6 feet. Specific gravities of the soil-grains were determined from fractions of three to six soil-tube samples. The mean value for the apparent specific gravity was determined from three to 50 samples. The extremes in porosity for any one locality commonly differ by 10 to 20 per cent of the mean. The soils varied considerably in texture as indicated by the moisture-equivalent, the coarsest textured one having an average moisture-equivalent of 4.2 with an average porosity of 43.3 per cent and the finest an average moisture-equivalent of 27.1 and an average porosity of 39.8 per cent. The porosities plotted against moisture-equivalents show no relationship whatever. Piper's conclusion is that the porosity does not increase with fineness of texture.

W. L. Powers (Oregon State Agricultural College) reports the study of the movement of water in small columns of soils taken in tubes from the field. So far as he has studied it, the specific gravities vary little and the weight per cubic foot is fairly uniform for one soil-type.

C. F. Shaw (University of California) emphasizes the great importance of the size and arrangement of pores and, as does Kittredge, points out the effect of cracks resulting from drying on the volume-weight. He states that since the moisture-content of the soil may affect the volume-weight of a soil in place so markedly, he has made fewer determinations of pore-space in connection with his field-studies than he otherwise would have done. He is of the opinion, however, that there is a consistent difference between the pore-space of coarse- and fine-textured soils within the same series and in pore-space between different horizons of the same soil-type. The surface-soil of the Antioch sandy loam has a lower volume-weight than columns of the heavy clay B horizon.

R. S. Smith (University of Illinois) refers to results of measurements of volume-weight of certain field-soils obtained by him and Harland [9], using the Israelsen [10] rubber-tube method. The results of 14 sets of volume-weight determinations upon soil-types were reported. The variation in volume-weights in the top 14 inches of soil was from 1.302 to 1.599, which on the assumption of a specific gravity of 2.65 gives a difference of about 11 per cent in porosity. The highest and lowest values were obtained from silt-loam, and the sandy loam, presumably, the coarsest textured soil reported, was about the average for all the soils tested. The conclusion is reached from these tests that clay-horizons are seemingly no lighter in weight than silty horizons, and possibly are heavier. Sandy horizons are probably heavier than fine-textured ones, though the data are not conclusive on this point.

F. J. Veihmeyer (University of California) reports that Edlefsen, Israelsen, and he have made many measurements of the volume-weights of soils of the Yolo series at Davis. Israelsen's study [10] included Yolo soils ranging in moisture-equivalent from 12.07 to 34.02, but he reported "no appreciable differences in average volume-weight were found, notwithstanding textural differences, the average volume-weight of several observations being 1.28." Israelsen also measured the pore-space of soils of typical farms in the Sacramento Valley of California which ranged from silt-loam underlaid with fine sandy loam to heavy clays. Israelsen [10] stated: "It is to be noted that the volume-weight varied from 1.10 to 1.75 and that the silt-loam soils are lighter than the clay-loams and clays. These observations are not in accord with the ideas generally entertained concerning the relation of volume-weight to soil-texture." He compared three methods of making volume-weight measurements, the paraffin-immersion [15], 6-inch diameter iron-tube, and the rubber-tube, and found that agreement exists between the results obtained by their use.

Veihmeyer and Edlefsen found no consistent differences in volume-weights of soils of the Yolo series at Davis, even though there is marked difference in texture. This conclusion is based on several hundred determinations. The soil-tube and paraffin-immersion methods were used. Veihmeyer and Hendrickson in connection with a study of the water-holding capacity of soils [20] measured the volume-weights of soils in one-foot increments to depths of 6 feet by using a soil-sampling tube [19]. Since some of the soils were tilled, the second and third foot probably are more indicative of the natural condition of the soil than the surface-layer. The average specific gravities of the soil-grains varied from about 2.60 to 2.74. Oakley fine sand with an average moisture-equivalent of 5.2 for the second and third foot had an average volume-weight of 1.42. Similar values are: Fresno sandy loam, 8.2, 1.37; Hanford fine sandy loam, 8.6, 1.34; Madera loam, 22.0, 1.32; and Yolo clay, 28.5, 1.30. The calculation of the porosity from these volume-weights show no significant differences. The values are the averages of about 50 samples for the moisture-equivalent and volume-weight.

E. Winters (University of Illinois), who has worked with R. S. Smith on Illinois soils, says that "using the same volume-weight data [9] leads to the conclusion that coarse texture usually is associated with low pore-space, though these pores usually are better adapted for drainage and percolation than in fine-textured soils."

It is apparent that there is difference of opinion among the contributors as to the relation of texture to porosity. Some of the data indicate larger porosity in coarse-textured soils than in fine-textured ones. Others showed the opposite trend. Most of the data, however, indicate that volume-weight and porosity are independent of texture. It is interesting to note that some beach-sands have approximately the same porosity as some clay-soils. Certainly, generalizations as to the relation of porosity and soil-texture are not justified at the present time.

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REPORT OF THE COMMITTEE ON UNDERGROUND WATERS, 1934-35

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The annual report this year consists almost wholly of a brief summary of investigations in progress in different parts of the country. It is by no means complete, and the Chairman of the Committee will be glad to receive information in regard to investigations that have not been mentioned.

The outstanding feature of the past year has been the focusing of public attention on problems of underground water, as a result of the drought-conditions, the activities of the National and State resource and planning surveys, and the creation of emergency-relief projects.

Mention should first be made of the reports prepared by the National Resources Board and the Mississippi Valley Committee of the Public Works Administration. Many members of the Section of Hydrology have had more or less direct contact with the preparation of parts of these reports. In fact, an apparent reduction in ground-water contributions on the program of the present session evidently is not due to any lag in interest but rather to the fact that many hydrologists have been so busily engaged in an administrative or advisory capacity on emergency-relief or planning projects that they have been unable to continue their fundamental studies. The published reports of the two boards mentioned, necessarily brief, have had wide circulation and have been abstracted in the press, and therefore they need not be discussed here in detail. The reports stressed one important fact, namely, that for large parts of the country there is a serious lack of information in regard to the ground-water supplies and the conditions under which they occur. Unfortunately, the detailed reports prepared by consultation of the National Resources Board and Mississippi Valley Committee have not yet been made public. It is to be hoped that eventually they may be published, for undoubtedly they contain valuable data hitherto unpublished, and it is especially desirable that factual data in regard to ground-water levels, consumption of ground-water, etc., be preserved in permanent form, where they may be readily available for comparison with conditions in the future.

Information from one source or another indicates that in at least one-third of the States the State geological surveys or other State organizations have been making ground-water investigations; and although definite information is not available it is probable that in other States investigations are in progress or are being considered under the stimulus of recommendations by National or State planning agencies. Some of these investigations relate principally to the geologic features of the ground-water supplies; others have involved drilling of wells for emergency purposes; and others have related more definitely to studies of hydrologic phenomena, such as fluctuations of the water-levels in wells. As examples may be mentioned an investigation in Ohio under the auspices of relief agencies which obtained information in regard to about 140,000 wells; extensive well-drilling programs in Missouri and other States hard hit by the drought; and a relief project in Monroe County, New York, by which a contour-map of the bed-rock surface was made in order to locate water-bearing deposits in the valleys.

The memorandum of O. E. Meinzer in regard to a program of recording fluctuations of lake and ground-water levels, published with the Chairman's report a year ago, was prophetic of a need that grew during the past year to entirely unexpected proportions. The severe drought of the summer of 1934 has given special impetus to inquiries as to the present position of the water-table compared to that of former years. More or less necessarily these inquiries are closely related to inquiries as to the stream-flow in 1934 compared to that of former years. Information bearing on these relations is given in the report of the Committee on Runoff and need not be duplicated here.

An extensive investigation of comparative ground-water levels was that made by Howard E. Simpson, State Geologist of North Dakota and a member of the Committee on Underground Water, which covered seven States in the Mississippi River Basin, results of which are summarized briefly in the reports of the Mississippi Valley Committee and the National Resources Board. On the basis of a questionnaire sent to 4683 well drillers in the Red River and middle Missouri River basins, from whom 1482 usable replies were received, it was concluded that there has been a progressive decrease in ground-water levels, varying on the average in the seven States from 8 to 17 feet, and apparently in places being more than 30 feet. In another study made by W. G. Hoyt of the United States Geological Survey for the Mississippi Valley Committee, the problem was approached through a consideration of stream-flow during drought-periods when the flow is all obtained from underground discharge. By this method it was found that during the severe drought of 1930-31 the flow of two streams west of the Mississippi River showed a relative decrease from that in comparable earlier droughts. In contrast it was found that in the more humid

parts of the basin east of the Mississippi River, stream-flow in drought-periods showed no significant evidence of a decrease in the ground-water runoff, and therefore, by inference, no lowering of the ground-water level.

Later the National Resources Board circularized the crop-reporters throughout the country for information as to the percentage of farmers not having water for their live stock in August, 1934, and steps have been taken to obtain similar data in the future. The results for 1934 have been summarized on a map that has not yet been published. The Board has also compiled information on localities where public water-supplies have been seriously diminished.

With widespread demand for information on comparative ground-water levels, attention is at present focused on the problem of the value of data in regard to water-levels available in different parts of the country, and of the information needed to interpret correctly the observed facts. To the layman, water is a simple thing, and his knowledge of it relates to simple phenomena, which may be easily comprehended. Therefore, it is perhaps not surprising that many persons--farmers, townsmen, well drillers, and even observers trained in branches of learning other than ground-water hydrology--essay to speak with authority on changes of ground-water level. Only those who have studied in detail the fluctuations of ground-water levels and the factors that produce them appreciate the errors that may result from inadequate observations and erroneous interpretations. Although much detailed information has been gathered in regard to fluctuations of ground-water levels, and some of it is in print, comparatively few hydrologists appear to know the variety of factors that produce fluctuations or the complexity of the resulting ground-water movements. There is little realization of the magnitude or rapidity of fluctuations that may result from seasonal or secular differences in rainfall, from differences in geologic conditions, in relief, and in depth at which the water lies, from differences in artesian and non-artesian conditions, from heavy pumpage in highly permeable formations or small withdrawals for domestic use in poorly permeable formations, and from changes in atmospheric pressure and other factors. The variety of fluctuations of the ground-water levels that have been revealed by automatic recorders installed on wells during the last 15 years has been amazing, and such records serve to emphasize the fact that conclusions as to secular changes in ground-water levels based on any information except actual measurements in wells may be quite erroneous.

Realizing the need for a more adequate guide to organizations concerned with fluctuations of the ground-water level in many parts of the country, O. E. Meinzer, Chief of the Division of Ground Water of the United States Geological Survey, in October, 1934, appointed a committee of geologists and engineers of that organization to consider the entire subject. The objectives of the Committee are the promotion of a proper and systematic development of a broad, if possible nation-wide program of observation-wells and, as far as practicable, the establishment of uniform field and office methods, which, however, may be modified as our knowledge increases. The Committee has devoted much time and careful thought to the preparation of a manual on the subject, which it is hoped will be completed shortly.

In accordance with the suggestion of Dr. Meinzer in last year's report of the Committee, attention has been given to the matter of obtaining information in regard to existing records of ground-water levels; but because of pressure of the Chairman's official work and lack of funds for the proper circularization of organizations and individuals that might have such records, it has not been possible to carry out this suggestion to any desired degree of completion. In response to a request from the Chairman several members of the Committee have sent in information in regard to organizations known to be making water-level measurements, and this will serve as a foundation upon which an expanding structure may be erected as contact is effected with more and more officials.

In reply to this request, C. S. Scofield called attention especially to the fact that the United States Bureau of Reclamation has been making observations of fluctuations of ground-water in Yuma Valley, Arizona, and of the water-stage in the nearby Colorado River since 1916. He also reported that the Division of Western Irrigation Agriculture, United States Bureau of Plant Industry, has made observations since 1922 at about 50 wells at its Newlands Field Station near Fallon, Nevada, and since about 1920 at 40 wells near its station at Huntley, Montana. M. R. Lewis also referred to general well-measurement programs of the Bureau of Reclamation in other States, and of the Division of Irrigation, Bureau of Agricultural Engineering, in connection with its studies of drainage-problems in irrigated areas.

Although definite information is not available, it is known that measurements of water-levels in wells have been carried on for several years in many irrigation-areas in California, and many of these measurements have been published in reports of the State Division of Water Re-

sources and its predecessor organizations. Among the longest records of water-levels in the western States is a series begun in southern California by the United States Geological Survey about 1900 and published in 1921 in Water-Supply Paper 468. That report contains a record of occasional measurements in one well from 1892 to 1901, more frequently in the next two years, and weekly measurements thereafter; and of another well since 1898. The well-measurement program in this part of California has been extended in recent years by State agencies. Doubtless many wells have been measured for considerable periods in other western irrigation States, but specific information in regard to them is not available.

A long series of well-measurements worthy of note is that made by the Department of Water Supply, Gas, and Electricity of the City of New York on the western half of Long Island. Weekly or monthly measurements were made in several hundred wells between 1904 and 1918, but the record is not complete for many of the wells. Unfortunately, the record was broken between 1918 and 1931, but many of the wells have been measured frequently since. It is interesting to note that a contour map of the water-table in part of this area was made in 1857. If the datum used for that map has been correctly correlated with that used for the more recent measurements, it shows that in 1857 the ground-water level was about as low as at any time since 1904. This fact is corroborated by general observations on the level of Lake Ronkonkoma, near the center of Long Island, which acts somewhat as a huge open well, and by the observed close relationship between the more recent observed ground-water fluctuations and the rainfall-curve. This curve shows a long period of deficient rainfall from 1831 to 1857, a period of 27 years, in 20 of which the rainfall was below normal. In spite of heavy pumpage, which in part of the area from 1904 to 1930 was equivalent to a total depth of about 15 feet of water, and in spite of low rainfall in a period of years ending in 1933, the water-level in some parts of the Island is now, after rainfall above normal in the last two years, about as high as at any time during the period covered by well-measurements.

The United States Geological Survey, largely in cooperation with States, counties, or municipalities, has made more or less periodic measurements on wells and maintained water-level recorders in the areas listed in Table 1.

Table 1--Wells on which periodic water-level measurements are made by the United States Geological Survey and cooperating parties (Correct for January 1, 1933)

Project	Wells equipped with automatic water-stage recorders	Wells measured periodically	Total
Arkansas	3	135	138
California (southern)	2	293	295
California (Mokelumne)	17	390	407
Florida	4	172	176
Hawaii	6	107	113
Idaho (Malad and Curley Valleys)	0	37	37
Idaho (Mud Lake area)	0	2	2
Idaho (Kootenai Valley)	2	335	337
Michigan	0	21	21
Montana (Flathead Valley)	2	43	45
Nebraska	1	101	102
New Jersey	24	143	167
New Mexico (Lea County	3	18	21
New Mexico (Mimbres Valley)	0	70	70
New Mexico (Roosevelt and Curry Counties)	6	36	42
New Mexico (Roswell Basin)	4	112	116
New York	5	165	170
North Carolina (general)	8	14	22
North Carolina (Elizabeth City)	1	60	61
Oregon	1	37	38
Pennsylvania	1	35	36
Texas	8	354	362
Utah (Ogden Basin)	8	21	29
Utah (Salt Lake City)	5	254	259
Virginia	4	1	5
Total	115	2956	3071

Certain measurements of some wells in the Roswell Area, New Mexico, in the Mokelumne and southern California areas, in Hawaii, and on Long Island are available for the years in the beginning of the present century or earlier. Of the other localities listed the Mud Lake Region, Idaho, has the oldest records, some of which were begun in 1921. Measurements were begun in several parts of the Coastal Plain of New Jersey in 1923; in the Roswell Area, New Mexico, in 1925; in the Grand Prairie Region, Arkansas, the Mimbres Valley, New Mexico, and the Memphis Region, Tennessee, in 1928; and in Texas in 1929. The other measurements have been started since 1929. Observations have been discontinued on some of the wells, but in some areas additional wells have been measured and more recorders installed. The total number of wells now being measured in the areas listed above is considerably larger than in 1933.

During the last year the United States Soil Erosion Service, in cooperation with the United States Geological Survey, has begun a program of weekly measurements on about 200 observation-wells on eight of its demonstration-projects in Kansas, Missouri, North Carolina, Oklahoma, South Carolina, Texas, Washington, and Wisconsin. Recorders have been installed on 28 of these wells. The chief purpose of this work is to study the effect of soil-erosion control-measures on fluctuations of the water-table.

This very brief and incomplete summary of existing well-measurement programs shows that throughout the country observations are being made on several thousand wells, with automatic recorders on perhaps 150 or 200 wells. Unfortunately there is a woeful lack of reliable records of ground-water levels in the great area of the interior agricultural States, where so large a part of the population depends on wells and where information in regard to water-levels is now so greatly needed. It is apparent that there is opportunity for further useful work in obtaining information in regard to existing long-time records of water-level fluctuations and of encouraging additional systematic observations. This subject is covered by a paper by Dr. Meinzer on the current program of the Section of Hydrology.

In view of the difficulties confronting the Committee in collecting information on this subject, the Chairman will appreciate it if anyone knowing of definite records of water-level measurements covering a few to many years will notify him, giving locality, purpose of measurements, period covered, whether or not results are published, and name of person who can give detailed information.

Another line of activity for the Committee suggested a year ago by Dr. Meinzer was a survey of the status of investigations of the permeability of porous media. In furtherance of this proposal during the year a preliminary study was made of features of this subject, and on March 1, 1935, Dr. Meinzer sent a questionnaire to about 60 investigators, asking for information in regard to methods used in making tests of permeability, methods of expressing results, purpose of tests, results that have been obtained, names of other investigators and testing laboratories, and other information. Replies have been received from about half of the investigators, and more are coming in. It has not yet been possible to analyze all the replies to the questionnaire, but this will be done during the coming year. The projects listed in the replies received include permeability-tests for the purpose of obtaining quantitative measurements of water or oil-bearing formations, studies of repressuring or flooding in oil-fields, studies of the correct spacing of wells, studies of the flow of gas through coal, engineering studies of earth and foundations, and studies of the suitability of material for dams. Pending a summarization of the questionnaire, mention of most of these studies may be omitted from the present report.

In replying to the questionnaire Morris Muskat and others report that a program of standardization of the permeability-units, as well as general precautions of technique, has been formulated and approved in code-form by the Topical Committee on Development and Production Research of the American Petroleum Institute. He states that, although the code was developed under the auspices of the oil-industry, those engaged in its preparation feel that it should be equally applicable to all fields involving the flow of liquids in porous media. This subject will eventually be discussed more fully in connection with the results of the questionnaire mentioned above. Dr. Muskat calls special attention to three papers as follows:

G. Hamel, Ground-water movements, Zs. angew. Math. und Mech., v. 14, pp. 129-157, 1934. This paper presents a rigorous treatment of a class of two-dimensional flow-problems involving free surfaces, the solution of which has not heretofore been available in the literature.

P. Nemenyi, On the validity of Darcy's law and its limitations, Wasserkraft und Wasserwirtschaft, v. 14, pp. 157-159, 1934. This paper gives a rather critical discussion of the experimental basis of Darcy's law and its range of validity. It also includes a reference to a third paper, by E. Lindquist, The flow of water through porous soil, presented before the Premier Congres des Grand Barrages, Stockholm, 1933.

Dr. Muskat also reports recent contributions from the laboratory of the Gulf Research Corporation as follows:

R. D. Wyckoff and H. G. Botset, An experimental study of the motion of particles in systems of complex potential distribution, Physics, v. 5, pp. 265-275, 1934.

Morris Muskat, Two fluid systems in porous media; the encroachment of water into an oil-field, Physics, v. 5, pp. 250-264, 1934.

Morris Muskat and R. D. Wyckoff, An approximate theory of water-coning in oil-production, Amer. Inst. Min. Metall. Eng. Petrol. Development and Technology, v. 114, 1935.

In connection with the permeability-studies V. C. Fishel of the hydrological laboratory of the United States Geological Survey has prepared a bibliography of about 500 titles relating to permeability and laminar flow. Unfortunately, funds are not at present available to publish this bibliography, but a few typewritten copies are being circulated as extensively as possible for corrections and additions.

The questionnaire relating to permeability has shown that in addition to investigators working on purely hydrologic problems those engaged in studies relating to the origin and recovery of petroleum are also showing much interest in this subject. There is continued interest by the petroleum-geologists and engineers in other problems of ground-water hydrology, and some of the problems and the work being done on them are discussed in a memorandum by F. H. Lahee attached as an appendix A to the present report. Attention may also be called to an extensive paper by Frederick G. Clapp on "Safety of water-flooding pressures at Bradford, Pennsylvania," which is to be published in the Bulletin of the American Association of Petroleum Geologists. This paper relates to the practical problem of the extent to which artificial water-intake pressure might be safely raised in the water-flooding process for rejuvenating the Bradford oil-field and involves interesting and new hydrologic problems.

Among miscellaneous studies reported to the Chairman of the Committee the following may be mentioned:

A paper by Willard Gardner, T. R. Collier, and Doris Farr entitled "Ground-water, Part 1, Fundamental principles governing its physical control," was published in November, 1934, as Bulletin 252 of the Utah Agricultural Experiment Station. This paper devotes considerable space to the mathematical approach to certain ground-water problems, especially to seepage of water under pressure and pumping for drainage. The authors have made a valuable contribution in applying methods of vector-analysis to problems of ground-water hydraulics. Another paper, Circular 106 of the Utah Experiment Station, by D. S. Jennings, Willard Gardner, and O. W. Israelsen, entitled "Seepage of ground-water and its relation to alkali accumulation," is of a more popular character and emphasizes the need of a wider control to obtain the maximum efficiency in use of the available supplies, not merely to prevent overdraft in some parts of a region but also to prevent water-logging in other parts.

In October, 1934, an investigation to determine the source, quantity, and character of ground-water obtained from the deeper wells in Iowa was started by the Iowa Geological Survey under an allotment of funds from the Emergency Relief Administration. The deep-well current-meter and salinity-apparatus developed by the United States Geological Survey are being used in an effort to find from what formations highly mineralized water is coming.

At the request of the United States Geological Survey a study of the relation of the size of well-screen slots to the yield of wells is being made in the hydraulic laboratory of the National Bureau of Standards. This investigation is being made primarily for the purpose of determining the type of screen best suited for installation in wells.

A memorandum by A. M. Piper, attached as appendix B to this report, describes several active ground-water projects in California, Oregon, and Washington.

Six papers relating to ground-water have been presented on the current program of the Section of Hydrology as a result of solicitation by members of the Committee.

United States Geological Survey,
Washington, D. C.

APPENDIX A--GROUND-WATERS IN OR ASSOCIATED WITH OIL-FIELDS

F. H. Lahee

This statement summarizes some hydrologic problems encountered in oil-fields and is based on a questionnaire sent to a group of about 15 geologists and petroleum engineers in the mid-continent and western parts of the country. Most of the replies indicated that insufficient data had been accumulated to permit adequate answer to questions, but a few contained some interesting information.

Taking of samples

Water-samples--Several of the companies have spent considerable money in procuring samples of water for analysis. Some of these samples are taken from shallow wells in order to locate areas of relatively high saline content, for in some regions these areas are significant of uplift. Other water-samples are taken from wells drilled for oil. We endeavor to take such water-samples at any time that the drilling well penetrates a strong water-bearing formation. Analyses of these samples may be useful later in the history of the well in locating casing leaks or bad cementing jobs, as upper waters may have a very different composition from water that underlies the oil as "bottom-water."

Our greatest difficulty in taking these water-samples is in obtaining them as nearly as possible with the same composition as they occurred in the rock-formations. They are very liable to be diluted by the mud used in drilling or by mixture with upper waters. In this connection I quote from the chemist of one company as follows:

"Oil-field waters should be sampled from the flow-line, as near as possible to the well and ahead of the point where chemicals may be added. Samples from the drain of the separator are good only after previous flushing of the drain and the accumulation of a new sample. In certain cases samples can be taken only from the flow-tank. Such samples should be carefully labeled with all pertinent information, indicating possibility of dilution or contamination. In no case should results on a tank-sample be taken as final. Water-samples from drill-stem tests should be taken from the bottom of the drill-stem only. Complete information concerning depth of test, amount of fluid, etc., should always be recorded. Water produced from a new well should not be considered a correct sample until the well has had ample time to clean itself. Even then check samples should be taken."

Cores--As it is not always possible to obtain water-samples, we, in the oil-business, make a special point of obtaining and testing cored samples of sands which may contain water, oil, or gas. It is usually true that a sand which contains oil has a very low chloride-content, but a sand at approximately the same depth which contains water has a high saline-content.

A comparison between cores of the same sand is used only in indicating these differences in a given pool or a given district, and we cannot extend the absolute figures outside of this pool or district. That is to say, in one district analysis may show a very low saline-content in an oil-bearing sand, whereas in another district the oil-bearing sand may show as high a saline-content as the water sands of the first district, but the water-sands of the second district have a still higher saline-content, or chloride-content. It is always true that we have to establish these relations by examination of cores from several wells before we can be sure that we are right in drawing certain conclusions concerning whether or not a sand is likely to yield oil or water.

The analysis of these cores is accomplished by a series of careful laboratory-procedures, involving calculation of total pore-space and several other steps that need not be enumerated here.

In obtaining cores for such analyses care has to be taken to avoid, as far as possible, contamination of the samples, especially by the drilling mud. The outer layer of a core may have its contained water greatly diluted by the fresh water of the drilling mud. In this connection I again quote from the chemist mentioned above, as follows:

"In present rotary-coring practice, the core as it is cut is held within the inner core-holder, the cutting-head being attached to an outer casing. Mud-fluid passes between the two pipes and through holes in the bottom connecting flange and impinges on the cutting-head and the section of core being cut. Theoretically the mud-pressure on the surface of the core should be equal at all points. However, the surging or jetting of the mud-fluid, which theoretically is absorbed and equalized immediately, is probably independently effective at the cutting-head, so

that a higher pressure is set up at the point where this fluid impinges than at other points in the core; and this difference in pressure allows the movement of drill-water through sections of the core, thereby washing a small portion of the interstices. Examinations of the cores have shown undoubted effect of the washing by the drill-mud, this effect in general, however, being confined to each end of the core and to a small area around the perimeter of the core. Where cores having a diameter of one inch or less are cut, this effect is greatly increased, and it is generally found that the largest portion of the core is washed.

"It is evident, therefore, that the reliability of the prediction of oil- or water-production on the basis of a core-test is somewhat limited in all cases. In most areas, though, a higher chloride-test is unquestionable indication of salt water.

"Low chloride-tests are adequate for a core-prediction only in so far as the evidence indicates no washing of the core. In a majority of cases there is a preponderance of evidence that the cores have not been washed. There would be very few doubtful instances of washing were we able to see the freshly taken cores. Definite predictions on cores which appear to be washed can be made only when the chloride-content is high, indicating thereby certainty of the production of salt water.

"Theoretically, by the above assumptions, the analysis of the leached residue of the core should be equivalent to the analysis of the actual water produced from the sand; but this relation does not work out in practice. The concentration of the constituents of the water as calculated from a core-analysis is always less than the concentration of the same constituents in the water; so undoubtedly some of the water is drained from the pore-spaces when the sample is brought from the bottom of the hole to the surface. This may be caused either by expansion of the fluid or by expansion of gases dissolved in the fluid."

Water-drive

Kansas, Oklahoma, and California--The replies from Kansas, Oklahoma, and California were not very satisfactory. There is evidently a great deal more that can be learned in these States if conditions are carefully watched. A reply from California states: "All our major fields have for some time past been under a rather strict proration, and I expect to find that there are comparatively few recent data available with respect to either water-encroachment or water-drive as the result of operations during the past few years."

Southwest Texas--One geologist reports that most geologists consider that the Greta Field, in Refugio County, Texas, is under a water-drive. But even here there are some who disagree. The Pettus Field, in Bee County, is reported to have no water-drive. Some of the wells were completely depleted without showing water. Geologists report that evidently what little water is present is merely encroaching passively and without exerting a driving force. This is thought to be due to the fact that the sand is lenticular. No definite water-table has ever been established in the Pettus Field.

In the Tuleta Field, also in Bee County, it is reported that there are streaks of salt-water sand here and there throughout the oil-bearing formation, and that sometimes the pores of the sand are found to contain both oil and salt water.

Rocky Mountain district--My correspondent in the Rocky Mountain district has written a very interesting description of conditions in several of the fields in Wyoming and Colorado. He refers to the Salt Creek Field, and I shall quote from his letter. (For a cross-section of this field showing the four sands mentioned, see Structure of typical American oil-fields, published by the American Association of Petroleum Geologists, v. 2, p. 600.)

"In the Salt Creek Field there are four main producing horizons which have been developed to a point where we know how the water will act. The First Wall Creek Sand has been a fairly active but delayed water-drive. Water has gradually come in and gone practically to the top of the anticline, but due to irregularities in the sand the hydrostatic head of the water varies greatly in different places. The water has never come in with such head to equal the original pressure of the oil and gas.

"In the Second Wall Creek Sand there is a head of water amounting to at least 2000 feet in the wells on the edge of the Field, but for reasons which have never been satisfactorily explained, this water has encroached almost none at all, and the area of the Second Wall Creek, which is the largest producing area by far in the Salt Creek Field, is barren of water, even though the pressure is now down to a very few pounds.

"In the Lakota Sand we have a very complete water-drive and flowing water displaces the oil every place in the structure. The Lakota production is relatively low at this time.

"Likewise, we have a good water-drive behind the oil in the Sundance Sand. The production in the Sundance Sand is not as far advanced as in other horizons, but we are very well satisfied that it will be a complete water-drive and the Sundance wells will never need to be pumped.

"At Iles, in northwestern Colorado, we also believe the Sundance Sand has a natural water-drive. The Field has been continuously prorated, and a relatively small amount of oil has been taken out, but we find that the bottom-hole pressures are practically the same all over the Field. We do not know whether this condition would be maintained if we pulled all the wells in large volume.

"In the Grass Creek Field, in the Big Horn Basin, the light oil-production is from the zone of Wall Creek sands, and here again we have a delayed water-drive. Water has come in to some extent, but in the nearly 20 years of production it has done little in maintaining pressure in the Field. On particularly porous open places the water has come in, so that various leases make considerable water, but the general pressure on the Field is very low.

"At Elk Basin the Wall Creek Sand has behaved similarly to the Second Wall Creek at Salt Creek. There is water around the edge, but it has not encroached, and now in the old age of the Field we find the best wells just above the water-level, where the oil has apparently settled by gravity.

"At Lost Soldier water did not flush the sands of the Wall Creek and did not invade the Dakota Sand. The Dakota production at Lost Soldier has gone over most of the structure, and the few producing wells in that horizon are pumping oil from the top of the old water-table on the edge of the Field. However, in the Lakota Sand, directly below the Dakota, the water appears to have encroached to a greater extent."

East Texas Field--There is no question that the East Texas Field stands out prominently as the pool where by far the most extensive study has been made of the problem of water-drive. As you are probably aware, the original pressure in the Field was about 1625 pounds to the square inch, the oil being found at depths averaging 3600 feet and the original down-dip oil-water contact being at 3320 feet below sea-level. Owing to the varying rates of production of the oil in the Field from the time it was discovered until the present date, it has been possible to make a very interesting study of the behavior of the Field, especially of the variations in pressure. There are a few geologists who still persist in believing that there is no water-drive in East Texas and who claim that the drive is accomplished by gas. However, what gas is present in this Field is in solution in the oil (I am excepting the very small gas-area in the south end of the Field, which is probably isolated from the oil), and this gas does not come out of solution until the pressure has dropped to somewhere near 740 pounds to the square inch. As the pressure is still above 1200 pounds to the square inch, the gas is all in solution.

A most interesting contribution was made toward the solution of this problem by the work of Ben Lindsley of the United States Bureau of Mines (U.S. Bur. Mines Rep. Inv. 3212, 1933). He has shown that the water-drive in the East Texas Field may be explained by the expansion of the water flanking the Field as the oil is withdrawn from the pool and as the pressures in the pool are reduced. It has been calculated that the extraction of the 600 million barrels of oil that have been produced to date in this enormous pool can account for some 12 or 14 feet of rise of the original oil-water contact. As the pressure is reduced in the Field, the water pushes in, owing to its expansion. There is apparently not the water-drive as formerly conceived--namely, a bodily flow of water through the sand from its outcrop all the way to the edge of the oil. This would be impossible because of friction; but there is an encroachment of the water, which is probably felt in the water-body most strongly close to the Field and less and less strongly away from it, until probably a few miles distant this tendency to expansion has as yet hardly been felt. That the conditions for such expansion have traveled westward, down the dip from the western edge of the Field, is indicated by the fact that a well drilled about eight miles west of the Field (a dry hole, without oil but with water in the Woodbine) showed a pressure 200 pounds lower than the original pressure of the Field.

I know from conversations with Dr. Meinzer last year that this problem of expansion has already been considered by hydrologists, but I do not know that there has ever been as thorough a study of it made, in connection with underground-water supplies, as in East Texas Field. (See R. J. Schilthuis and William Hurst, Variations in reservoir-pressure in the East Texas Field, Oil Weekly, October 15, 1934, p. 24.)

Problems of petroleum geology

Several papers on oil-field waters are contained in the recently published Problems of petroleum geology (Tulsa, Amer. Petrol. Geol., pp. 833-985, 1934).

Sun Oil Company,
First National Bank Building,
Dallas, Texas

APPENDIX B--ACTIVE GROUND-WATER PROJECTS IN CALIFORNIA, OREGON, AND WASHINGTON

A. M. Piper

General

Pumping from wells for irrigation--The Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, is investigating the economics and practice of pumping from wells for irrigation in the western United States. The study is under the charge of Carl Rohwer. Its aims are (1) to gather data pertinent to the practical and economical phases of pumping for irrigation, including mechanical units, wells, methods of pump-installation, the assembled plant, and the efficiency of the various units, and (2) to compile all available information on methods and cost of well-drilling and the numerous factors influencing them, such as various types of casing and relation of diameter of casing to yield. The field-work on both phases of the study is about complete. The manuscript on the first phase of the project is in process of preliminary editing. It is intended to publish the results of the study in two bulletins, probably as Department circulars.

California investigation by United States Department of Agriculture, Bureau of Agricultural Engineering

Storage of water underground by spreading--The Division of Irrigation, through A. T. Michelson, has continued its study of storing water underground by spreading. The chief purposes of this study are (1) to determine the rate of percolation of water through the various types of soils prevailing in the areas where water-spreading is feasible, (2) to determine the effect of temperature of soil, water, and air on this rate, (3) to ascertain by experiments whether or not the native vegetation on these areas is beneficial through stimulation of percolation due to root-action, (4) to determine, by experimenting with plots over ascending and descending water-tables, the effect of the fluctuating water-table on the rate of percolation and when the soils refuse further charge, and (5) to learn about movement of water laterally and vertically through soils of these types and determine to what extent silty water affects percolation. The several large spreading "cones" of southern California are being surveyed for wetted areas during spreading seasons, and suitable water-measuring devices have been installed, with continuous water-stage recorders. Several short papers have been prepared reporting preliminary findings. Material is being compiled for publication as a technical bulletin of the United States Department of Agriculture during the fiscal year 1936.

Studies of similar scope are possible in Arizona, Idaho, Oregon, Utah, and Washington.

Investigation by United States Department of the Interior, Geological Survey

Mokelumne Area--The Geological Survey, in cooperation with the East Bay Municipal Utility District, has continued its investigation into the possible effect of regulation of the Mokelumne River and of diversions from that stream upon the recovery of ground-water from adjacent land on the valley-plain, in central California. In the past year measurements of stream-flow have been continued by the Geological Survey and measurements of ground-water levels have been kept up by several collaborating agencies. However, stress has been laid on the preparation of a report to coordinate findings from 1926 through 1933.

Investigations by California Department of Public Works, Division of Water Resources

South Coastal Basin--The investigation by the Division of Water Resources in the South Coastal Basin of California is designed to give information as to the ground-water storage-capacity, utilization of water, and deficiency or surplus of water in each of the 35 ground-water districts that make up the Basin. This investigation has now continued four and one-half years, and 13 reports published since its inception include all pertinent data (San Gabriel investigation--basic

data, 1923-28, California Div. Water Rights, Bull. 5, 1927; San Gabriel investigation--basic data, 1926-28, California Div. Water Rights, Bull. 6; San Gabriel investigation--analysis and conclusions, 1929, California Div. Water Rights, Bull. 7, 1929; Santa Ana investigation, flood-control and conservation, California Div. Engineering and Irrigation, Bull. 19, 1928; South Coastal Basin, a cooperative symposium of activities and plans of public agencies in Los Angeles, Orange, San Bernardino, and Riverside counties leading to conservation of local water-supplies and management of underground-reservoirs, California Div. Water Resources, Bull. 32, 1930; Rainfall-penetration and consumptive use of water in Santa Ana River Valley and Coastal Plain, California Div. Water Resources, Bull. 33, 1930; South Coastal Basin investigation, records of ground-water levels at wells, California Div. Water Resources, Bull. 39, 1932; Records of ground-water levels at wells for the year 1932, seasonal precipitation-records to and including 1931-32, California Div. Water Resources, Bull. 39-A (mimeographed); Records of ground-water levels at wells for the year 1933, precipitation-records for the season 1932-33, California Div. Water Resources, Bull. 39-B (mimeographed), 1933; South Coastal Basin investigation, quality of irrigation-waters, California Div. Water Resources, Bull. 40, 1933; Value and cost of water for irrigation in Coastal Plain of southern California, California Div. Water Resources, Bull. 43, 1933; Water-losses under natural conditions from wet areas in southern California, California Div. Water Resources, Bull. 44, 1933; South Coastal Basin investigation, geology and ground-water storage-capacity of valley-fill, California Div. Water Resources, Bull. 45, 1934).

The following quotation is taken from the latest of these reports (Bull. 45, p. 19): "The geological investigation has not been concerned with the actual determination of overdrafts or surpluses in the various ground-water basins, but rather it has been carried out for the purpose of determining, first, the geological conditions, including the nature of the basin-boundaries, the physical character of the basins themselves, and their relation to the occurrence and movement of ground-water, and, second, storage-capacity estimates for each basin, in order that the rise and fall of the water-table can be interpreted in terms of storage-changes.

"The geological investigation included several lines of study. These are outlined briefly as follows:

"Experimental work--Several hundred samples of typical gravels, sands, and clays of the South Coastal Basin were dug from surface-exposures and obtained from post-hole borings. About 2000 samples of similar materials were collected from wells as they were being drilled. Porosity-determinations were made of the samples taken in place and of those which came intact from wells. Further experimental work was done to determine the water-yielding capacity of various materials, and the coarser sediments were classified by mechanical analysis.

"Subsurface studies--About 5000 well-logs from all parts of the Basin were collected. Nearly 300 wells were observed as they were being drilled. The well-logs were grouped and the materials classified with the aid of notes from wells observed during drilling. Thus by grouping the well-logs and averaging the materials, the vertical and horizontal distribution of water-bearing materials was estimated. Combining this information with yield-values obtained by the experimental work, storage-capacities of the basins were computed. The well-logs were used further to determine, where possible, the contour of the bed-rock floors of the basins."

Southern San Joaquin Valley--Measurements of depth to water in wells have been made in the fall of each year in Kern, Tulare, Kings, Fresno, Madera, and Merced counties. Publication is not contemplated, but initial data have been utilized in a previous publication (San Joaquin River Basin, California Div. Water Resources, Bull. 29, 1931). It is contemplated that the program will be continued indefinitely.

Sacramento Valley--In analogous fashion, measurements of depth to water were made in the fall of each year in all the Sacramento Valley north of Stockton. Again, the program of measurements will presumably continue indefinitely; publication is not contemplated, but initial results have been utilized (Sacramento River Basin, California Div. Water Resources, Bull. 26, 1931).

In recent years the Division of Water Resources has studied ground-water problems in Santa Clara County (Santa Clara investigation, California Div. Water Resources, Bull. 42, 1933), in Salinas Valley, Ventura County (Ventura County investigation, California Div. Water Resources, Bull. 46, 1933; Ventura County investigation, basic data for the period 1927 to 1932, inclusive, California Div. Water Resources, Bull. 46-A (mimeographed), 1933), and in the Mojave River Basin (Mojave River investigation, California Div. Water Resources, Bull. 47 (mimeographed), 1934). Local agencies are continuing measurements of water-levels at wells in each of these areas, according to the program established by the Division.

Oregon

Harney Basin--The cooperative investigation in the Harney Basin (Trans. Amer. Geophys. Union, 13th annual meeting, p. 310, 1932; Trans. Amer. Geophys. Union, 14th annual meeting, p. 377, 1933) has been reported in a manuscript which is now being edited and which discusses the feasibility of pumping from wells to irrigable land on a central alluvial plain. The most critical factor considered has been the safe yield of the area under its desert-environment. The investigation was made in cooperation between the United States Geological Survey and the Oregon Agricultural Experiment Station.

Walla Walla Basin--The possible role of ground-water in a comprehensive scheme for most effective use of all water-resources in the Walla Walla Basin of Oregon and Washington has been investigated by the United States Geological Survey in cooperation with the State Engineer and the Agricultural Experiment Station of Oregon, the Umatilla County Court (Oregon), and the Washington Department of Conservation and Development. A fact-finding report has been released to the public (Ground-water in the Walla Walla Basin, Oregon-Washington, U. S. Geol. Surv. typoscript report, October 30, 1933).

Washington

During the last year water-supplies for a large percentage of the municipalities in the State of Washington have been investigated by the Division of Geology of the Washington Department of Conservation and Development, cooperating with the Agricultural Experiment Station of the State College of Washington and the State Department of Health. The work has been directed by H. E. Culver, Supervisor of Geology. Its purpose has been to compile available information as to location, source, character, amount, and related geologic features of municipal water-supplies. Reports have been received from about 200 municipalities, and maps have been prepared to show certain groups of the data obtained. Publication is intended, although specific plans have not yet been made.

At the suggestion of the water-resources division of the State Planning Council and under an authorization by the Washington Emergency Relief Administration, a project was begun in January, 1935, to transcribe and study well-records that were made available to State authorities through the cooperation of drillers and other interested persons. The compilation was made by Raymond Farr, directed by S. L. Glover, of the Division of Geology. The available well-logs were thought to run back for about 30 years, but it appears that a very large number of those for years prior to 1923 have been destroyed by fire. Altogether, however, several hundred logs were obtained and compilation was begun. At present, work has been suspended owing to lack of funds. Ultimate publication is contemplated.

U. S. Geological Survey,
Lodi, California

REPORT OF THE COMMITTEE ON DYNAMICS OF STREAMS, 1934-35

Lorenz G. Straub, Chairman

Nearly all of the members of the Committee on Dynamics of Streams have during the past year been actively engaged on research-problems of one type or another directly bearing upon the functions for which the group was established. The Committee fostered the preparation of eight of the papers presented this year at the annual meeting of the Section of Hydrology. A consistent effort has been maintained to keep in touch with other groups interested in research of the character sponsored by the Committee.

A number of developments have occurred in other organizations whose activities are more or less closely related to those of the Committee on Dynamics of Streams. The Applied Mechanics Division of the American Society of Mechanical Engineers is now publishing a journal containing the results of theoretical investigations and research reviews in fluid mechanics [see reference 1 in section "Bibliography"].

The American Society of Civil Engineers has recently formed a Special Committee on Hydraulics Research, the attention of which at the present time is directed toward the field of open-channel flow, river-hydraulics, and hydraulic similitude. This group has for the present been organized into three subcommittees [2] concerned especially with (a) glossary and symbols to be used in hydraulics research, (b) checking conformity of model studies to prototype performance,

and (c) the encouragement of the preparation of papers relating to hydraulics research. An excellent service is being rendered by the hydraulics laboratory section of the National Bureau of Standards in the publication of a bulletin [3] giving the status of current hydraulic-research projects in the various laboratories throughout the United States.

Current research

The last report of this Committee on the current activities and publications in the field of dynamics of streams and related subjects was presented at the annual meeting of the American Geophysical Union in April, 1933 [4]. Since this time greatly accelerated activity has been evident in the field of stream-dynamics. This development is doubtless partly due to the economic situation of the country which has led to the development of the natural resources, and, consequently, a broad interest in the phenomena of soil-erosion, equilibrium-conditions of natural watercourses, etc.; but also due to the research-activity in the various fields of fluid mechanics which have lain dormant until comparatively recent years.

Ice-formation in rivers

A number of reports have appeared on the general subject of ice-formation in rivers. A careful analysis was made of the effects of ice on the flow of the Upper Mississippi River [5]. Studies have also been published concerning the winter regimen of the Walchow River [6] showing the influence of the form of the stream-bed upon the occurrences of ice-blockades. Theories have been presented of ice-formation [7]; also a discussion of the physical structure of water and ice, giving consideration to the various types of ice [8] in rivers. The influence of ice-formation upon the longitudinal profile [9] of a watercourse has been discussed in detail. Articles have appeared discussing developments in German rivers, including the effect of ice-glaciers upon the stream-valley formation in northern Germany [10], and ice-observations on the Isar River [11]. The backwater due to ice and resulting winter floods in the Narwa River [12] are reported.

Discharge-formulas and roughness-coefficients for open channels

Critical studies have been made of the various open-channel flow-formulas. In one case a comparison is made of the velocity-formulas of Ganguillet and Kutter, Bazin, Biel, Strickler, Darcy, Weisbach, Prony and Flamant, Hazin and Williams [13]; a shortened form of the Bazin formula was proposed [14]. A monographical presentation of the Forchheimer velocity-formula to determine the discharge through circular cross-sections filled to various depths, and for rectangular and trapezoidal cross-sections, the latter having various side-slopes, was published [15], also an investigation of the relation of mean depth to roughness-coefficient in the Ganguillet and Kutter formula [16]. A report was made at the world power-conference on velocity-formulas for open channels giving a discussion of the original and a critical analysis of the commonly used equations [17].

Proposals have been made for the analysis of flow-conditions in open channels with varying roughness of walls [18], a formula for the computation of the mean roughness and profiles for various border roughnesses being derived; charts have been prepared in a study of separate roughness-coefficients [19]. Studies of the discharge-relation have also been made for natural streams [20], artificial channels of a particular type used in Germany in the Emscher and Lippe districts [21], also of the flow in channels with curvilinear cross-sections [22], and of the influence of irregularities of side-slopes and bed upon the capacity [23, 24]. Studies made in Austria show the effect of temperature upon flow in open channels so minute as not to be measurable by ordinary methods [25]. Another publication is directed toward showing that in the case of natural watercourses no definite, non-variable law exists between the velocity and the function of the mean depth, each type of cross-section requiring a different velocity-function [26].

Sediment-transportation by rivers, bed-load, suspended load, scour, soil-erosion

The many problems connected with the development of rivers and harbors have done much to encourage extensive studies of the mechanics of sediment-transportation by flowing water, particularly experimental studies. A review of the silt-problem as related to rivers, presenting numerous data of the silt-transportation, the sedimentation of reservoirs, and the like, formed a report [27] presented under the auspices of the Special Committee on Irrigation Hydraulics of the American Society of Civil Engineers. Numerous papers concerning the suspended matter moved by individual rivers have appeared; these include silt-observations at various sections of the Iller Canal [28], suspended matter transportation of the Lech [29], investigations of the bed-load and suspended load of the Inn River [30, 31], the Danube [32]. Discussions have appeared of the

solid material transported by rivers [33, 34], also a discussion of the quantity of earth which may be transported by a watercourse has been given with experimental verification by laboratory studies [35,36]. Extensive experiments were made of the bulk-volume of silt in nature as well as under laboratory-conditions [37].

The subject of bed-load movement has been a particularly mooted one with considerable experimental study; a number of American hydraulics laboratories have been giving considerable attention to bed-load movement [38]. Sustained interest is also evident in Europe. Experiments on the transportation of sediment of uniform grain-size were made at the University of Zurich [39] and other institutions. Other papers were concerned with the sources of sediment transported in rivers [40], the measurement of bed-load quantities in rivers [41], and the movement of bed-load in natural watercourses [42, 43, 44, 45]. Discussions of the nature of bed-load movement have appeared as a result of experimental studies [46, 47, 48]. There have also been investigations on the movement of bed-load in a forked flume [49].

Experimental and analytical treatments of the problem of erosion in movable bed-streams have been published, including experimental checks of the Exner erosion-equation [50], presentation of a general equation determining deformations of erodible stream-beds [51], the occurrence of scour upstream of weirs and pier-heads (model experiments) [52], retrogression of levels in riverbeds below dams [53], analytical studies of the equilibrium-conditions of débris-laden streams [54], a study of the longitudinal profile of streams and rivers which transport bed-material by arriving at an equilibrium-condition between scouring force and size of sediment-particles [55]. Studies have also been published concerning the conception of the "bed-forming water-stage" for rivers [56], the development of a movable bed-stream indicating the dependence of the talweg upon the relative height of the shore to the normal water-surface [57], and the influence of the tributary bed-load upon the form of the normal profile of canalized river-stretches [58]. Observations have been reported of the action of water flowing over the surface of gravel-bars in the Inn River [59]; the results of observations on the Rhine upstream of Lake Constance are used as a basis for suggesting methods of treating torrential streams [60]. The results of analytical and experimental studies together with observations in nature have been reported showing the effect of channel-contraction works upon the regimen of movable bed-streams [61]. Objections based upon experimental studies has been made to the usual explanation of the mode of transportation of bed-load around river-bends [62].

A number of studies have been made concerning sedimentation of materials in more or less still water. A hydrometer method of determining the mechanical composition of soils and other materials has been developed [63]. An analysis has been given of the factors entering into the size-distribution of particles within water-laid sandstone [64]; other investigations included studies of the system of vortices formed behind a sphere moving through viscous fluid [65] and model-experiments to determine the water- and silt-movement in harbors [66].

Federal interest in soil-erosion studies has brought this character of research to the fore with such enthusiasm that a subcommittee (of the Committee on Dynamics of Streams) was formed specifically for the purpose of coordinating and making available research-material on this subject. Some of the more important phases were considered at the 1934 meeting of the American Geophysical Union. Discussions were presented on records of silt carried by the Rio Grande [67], dynamic action of rains in relation to erosion [68], dynamics of erosion in controlled channels [69], charting the effects of erosion [70], choking of pore-space in soil by erosion-effects [71], erosion-acceleration [72], absorption of rainfall and its relation to runoff and erosion [73], basis for developing practical methods for erosion-control [74].

Working models in the solution of stream-dynamics problems

Probably in no field of river-dynamics has there been more enthusiastic activity than in that of research by means of small-scale models. Discussions have appeared of the practical phases of river laboratory-hydraulics [75], and also upon the verification in nature of laboratory-results [76]. The question of the use of models as aids in design and construction formed the subject-matter of a two-day conference of the Society for the Promotion of Engineering Education at its annual meeting in Ithaca, New York [77]. The publication of the results of many specific model-studies, as well as the presentation of the principles of similitude, have appeared within the past two years. It is generally recognized that perfect similarity is seldom obtainable, particularly in the class of fluvial models [78, 79, 80, 81, 82]. Important experimental studies of scale-effects are being made [83,84]. Specific studies related to stream-dynamics in progress are far too numerous to be mentioned at this time [3].

Potential flow, flow around obstructions, flow in curved channels, etc.

A number of treatises have appeared on the subject of applied hydrodynamics which do much to fill a need felt for many years [85, 86, 87]. Experiments were performed in Hanover to observe the flow-conditions around bridge-piers [88]; other investigations (bridge-piers) were made of several models of rectilinear cross-sections with semicircular ends, the ratio of length to breadth having various values from ten to one [89]. Analytical studies included that of the movement of eddies past a groin [90], the application of the energy-gradient to a fluid mass of finite cross-section [91], application of the potential theory to the movement of water in curved canal or river-conduits [92]. An analysis was made using the general flow-equations for viscous fluids under the assumption that rigid spherical particles are freely transported, showing that the pressures and flow are dependent upon the quantity and dimensions of the rigid particles [93]. A method was developed [94] to observe fluid flow by means of an ultra-microscope allowing photographic recording. A number of experimental and analytical studies have appeared concerning the flow in curved channels [95, 96, 97].

Non-uniform flow in open channels

Several valuable contributions have been made on both stationary and variable non-uniform flow in open channels, some of which are referred to elsewhere in this report. Several phases of the subject are treated by a Swiss publication [98]. Other more specialized publications include graphical methods [99, 100], analytical treatment of the effect of a step in the bed of a stream [101], studies of stationary non-uniform flow in open channels [102], problems involving side contractions [103], backwater-curves [104, 105], etc. Variable-flow studies are involved in the determination of discharge-relations in tidal districts [106, 107].

Phenomena of hydraulic jump, hydraulic rollers, etc.

The occurrence of water changing its flow-conditions through the energy critical has been given much attention. Detailed studies of the length of the hydraulic jump in rectangular channels were made at Columbia University [108], also in Germany [109, 110]. A discussion appeared concerning the method of energy-dissipation in the hydraulic jump [111], the question being whether the energy-dissipating action of the surface-roller is entirely dependent upon its volume, or whether the roller is at all responsible for energy-dissipation. Other studies included the hydraulic jump in inclined progressively broadening channels [112].

Flood-movements, wave-motion, stage-oscillation in watercourses

Several valuable contributions have recently been made on the subject of wave-motion and related phenomena. One of the more complete treatments [113] concerns the review of laws governing a steady flow in open channels, uniformly progressive flow, the dynamic propagation of stable wave-forms, the use of hydraulic models for solving problems in unsteady flow, routing of flood-waves in actual rivers, etc. Other studies which have been published concern surface-waves under various conditions, also waves in a canal having mild variations in breadth and depth [114, 115], the generation of waves in a canal by the movement of a transverse wall [116], and several other wave-motion studies in channels [117, 118]. Experimental studies have been performed to arrive at the basic principles for the computation of wave-velocity, the form of wave-crest and water-surface position, in the case of flood-waves in completely dry river-courses, such as would occur in the case of rupture of a dam [119]. Experimental verifications of the Kelvin formula for the propagation of waves where capillarity and canal-depth are taken into account have been reported [120]; a simple derivation is presented of the Airy formula for the velocity of propagation of waves in water of finite depth [121]. A new method has been presented for the determination of surface-tension from observations of the wave-length and frequency of capillarity-waves at the water-surface [122]. Investigations are in progress of wave-action on sea-walls, these being both analytical [123] and by means of models [124]. Studies have been made of stage oscillations in ocean-bays as a result of tides [125], and also because of the influence of variations in atmospheric pressure [126]. Studies of short and long-time stage-prediction for rivers, the computation of discharge-duration curves, the analysis of long-time records of stream-flow and their influence upon the stream-bed have been the subject of a large number of papers [127, 128, 129, 130, 131, 132, 133, 134].

Turbulence

Definite progress is being made in the analytical and experimental research of turbulence. The Kaiser Wilhelm Institut für Strömungsforschung in Göttingen under the direction of L. Prandtl, and the California Institute of Technology under Th. Von Kármán have made especially important

contributions [135, 136]. Prandtl discusses the cause of the occurrence of turbulence, the flow along a rough wall, the velocity-distribution, etc. Studies of the Kármán similarity-hypothesis [137] in the theory of turbulence have been made, also the application of statistical mechanics to the theory of turbulent fluid motion [138, 139, 140], analysis of turbulence in channels of infinite breadth [141]. A recent report has been published giving the results of investigations at the California Institute of Technology [142] of turbulent flow by means of the hot-wire anemometer; several other pertinent studies of turbulence have been made recently [143, 144], including an application to flow-occurrences in natural rivers [145]. Progress apparently has been made in setting up expressions showing the relation between turbulence and the transportation of suspended material by streams [146, 147, 148].

Viscosity-influences

It is becoming generally recognized that, although one might be concerned only with a single fluid, water, in the study of dynamic problems of streams, the influence of viscosity should be taken into account in experimental work as well as in analytical treatment. Viscosity of water varies considerably even within the normal range of temperatures found in rivers. Viscosity influences the capacity for transportation of suspended load, also the character of flow, especially at low velocities. A French treatise has appeared recently summarizing the newer theoretical basic views regarding the nature of viscosity of fluids [149]; studies have also been published concerning the flow of liquid suspensions [150], the computation of internal friction of viscous fluids containing rigid particles in suspension [151], studies of and variations in the Oseen resistance-tneory concerning laminar flow [152], kinetic theory of internal friction [153], stream-line and turbulent flow in open channels [154], laminar sheet-flow [155].

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REPORT OF THE COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1934-35

C. S. Howard, Chairman

The membership of this Committee is as given in the Transactions of the Fifteenth Annual Meeting with the addition of I. A. Denison, National Bureau of Standards, Washington, D. C., and with the exception of Messrs. Flynn, Logan, and Sale who have resigned from the Committee.

Analyses of a number of highly mineralized waters from Oklahoma and Kansas are given by Case in the paper "Subsurface-water characteristics in Oklahoma and Kansas" published in the August 1934 Bulletin of the American Association of Petroleum Geologists. "All the waters of this region are shown to be of a single type and much alike in concentration from Ordovician to Pennsylvanian. Three localities show marked differences in the water of Ordovician age. These differences may have been caused by dilution from the outcrops. Local variations occur in the waters of all water-bearing formations. The more important of these are shown by analyses and curves."

The quality of the surface- and ground-waters of the San Joaquin Valley of California is discussed in a recent report by Eaton. The report "Boron in soils and irrigation-waters and its effect on plants with particular reference to the San Joaquin Valley of California" was published as Technical Bulletin 448 of the United States Department of Agriculture. The following is an abstract of sections of the report: "Surface-waters originating in the high Sierra Nevada which form the eastern boundary of the great structural trough known as the San Joaquin Valley were found to contain relatively low concentrations of boron, usually in the order of 0.1 and 0.2 part per million. As has previously been established, the salinity of these waters is remarkably low. Taken as a group the ground-waters east of the valley axis, marked by the beds of Buena Vista and the now dry Tulare lakes, the Kings River Slough, and the San Joaquin River, likewise contain little boron and they are for the most part relatively low in other salt constituents. In these waters the sum of the milligram-equivalents of calcium and magnesium is almost always in excess of sodium, and the bicarbonate-concentration usually exceeds the sum of chloride and sulphate. The quality of these waters thus reflects the water-resistant granitic, metamorphic, sedimentary, and igneous formations of pre-Cambrian age that characterize the high Sierra Nevada and the valley-fill brought down from these mountains. By far the greater part of the water entering the valley is derived from the Sierra Nevada watershed.

"Shorter streams rising in the Tehachapi and San Emigdio mountains that form the southern boundary of the valley and in the Coastal Mountains that form its western boundary contribute relatively little water to the valley-floor except after flood-time. These waters, reflecting in their compositions formations relatively free from granitic and similar formations but instead soft serpentines, shales, and sandstones of Cretaceous age, are more highly mineralized than those from the Sierra. Boron is commonly found in concentrations of one or more ppm. The water from shallow wells west of the valley-axis reflects the quality of the surface-water in salinity in that boron may be present to the extent of one ppm or more. Bicarbonate is commonly exceeded either by chloride or sulphate or both and the concentration of sodium tends to be less than the sum of calcium and magnesium, that is, the percentage of sodium is commonly less than 50.

"Wells drilled to depths of 500 to 2000 feet, of which there are many both along the axis of the valley and to the west, produce water with highly variable concentrations of boron. These deep-well waters do not clearly reflect the sources from which they are derived. Commonly the total salinity is less than that found in shallower wells and the percentage of sodium tends to exceed 50 and oftentimes 80 and 90.

"In many of these deep wells, particularly those in the bed of the old Tulare Lake, but also to the south as well as in the Lodi and Stockton areas, the sulphate-concentrations are remarkably low. Concentrations below 0.05 milligram-equivalents per liter are found."

Some new analyses of natural waters and also of treated waters are given in United States Geological Survey Water-Supply Paper 658, "The industrial utility of public water-supplies in the United States, 1932," which was issued in August 1934. The report gives analyses showing the composition of the public water-supplies of 670 places which serve 56,000,000 consumers.

The investigation on the corrosion of ferrous metals by soils has been continued by the National Bureau of Standards during the past year. These studies show no direct relation between the resistivity of the soil and its corrosiveness within a limited range of resistance-values. The composition of the soluble material in the soils, however, has an important influence on their corrosiveness. Soils which had caused corrosion in the field-tests when extracted

with water in the laboratory showed a predominance of sodium as sulphate and chloride and the practical absence of the bicarbonates of calcium and magnesium. In the case of several corrosive soils, calcium sulphate was also present in considerable quantity. Non-corrosive soils, however, contain calcium and magnesium bicarbonates with very small quantities of sodium salts.

Many abandoned mines in West Virginia, Pennsylvania, and Ohio were sealed during the past year in an attempt to prevent pollution of streams by acid-waters draining from these mines. A number of mines have been sealed and studies have been made to determine the effectiveness of the work. In West Virginia, according to a preliminary report of the State Board of Health, over 4000 openings in 205 abandoned mines were sealed during the year. Laboratory-tests on samples from some of the streams show acid-reductions of 25 per cent. It is estimated that there are over 3000 openings in West Virginia that should be sealed. In Ohio, Pennsylvania, and other states there are a large number of mine-openings which should be sealed to prevent acid-pollution of the streams.

Mr. Leitch makes the following suggestion in regard to the studies of acid waters: "Due to the poisoning effect of iron sulphates, we have found that most apparatus designed for field-estimations of hydrogen-ion values are not suited to mine-waters. We have recently shown that the glass-electrode is adaptable to that type of water and are now trying to develop a portable vacuum-tube apparatus using that principle."

The chemists dealing with sea-water on the Pacific Coast have recommended the use of a milligram-atom in reporting the constituents of sea-water. A milligram-atom is equal to the number of milligrams of the element determined, divided by its atomic weight. This recommendation was made in the paper "The reporting of data in oceanographical chemistry" by N. M. Carter, E. G. Moberg, T. Skogsberg, and Thomas G. Thompson (Proc. Fifth Pacific Sci. Cong., pp. 2123-2127, 1934).

The amount of manganese in sea-water has been determined by Thompson and Wilson using sodium paraperiodate. With this reagent it is possible to detect variations of 0.18×10^{-4} milligram-atom of manganese. This was reported in the paper "Occurrence and determination of manganese in sea-water" by Thomas G. Thompson and Thomas L. Wilson (J. Amer. Chem. Soc., v. 57, pp. 233-236, 1935).

A reference to problems of quality of water as related to oil-production is given in a memorandum by F. H. Lahee which appears as an appendix A to the report of the Committee on Underground Water. A report "Seepage of ground-water and its relation to alkali-accumulation" is mentioned in the report of the Committee on Underground Water.

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P A P E R S

THE FLOW OF WATER IN THIN SHEETS

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(Published with the approval of the Director as Research Paper No. 131 of the Idaho Agricultural Experiment Station)

The experiment reported herein was carried on by the authors during the year 1928 at the University of Idaho. Most of the observations and computations were made by the junior author and the original report was prepared by him.

A mathematical analysis of the application of irrigation-water requires knowledge of the rate of infiltration of water into the soil, of the velocity of flow over the surface, and of the factors governing these two phenomena. Studies on the rate of infiltration have been published heretofore (Agric. Eng., v. 9, pp. 147-148). Little work appears to have been done on the flow of water in thin sheets such as occurs in the strip-border method of irrigation.

The law governing uniform, steady flow of water in open channels is usually expressed by a formula of the type

$$V = KR^M S^N$$

in which V is the velocity, R is the hydraulic radius, S is the slope of the water-surface, K is a coefficient which varies with the roughness of the channel (sometimes considered to vary with R and S also), and M and N are exponents usually considered constant for all velocities causing turbulent flow.

It appears probable that the flow of water in thin sheets follows the same law as the flow in channels. This experiment was therefore designed to determine values for the coefficient and exponents in the general formula. The method was to allow a shallow stream of water to flow over the surface of Palouse silt-loam soil contained in a trough or flume.

The flume, of wooden construction lined with sheet metal, was 20 feet long, 1.90 feet wide, and 1.5 feet deep, inside dimensions. The upper end and center were equipped with jack-screws so that any desired slope could be obtained.

To measure the quantity of water flowing, a set of free orifices cut in a brass plate fixed in the side of a metal tank was used. The tank was constructed so that the head upon the orifices was maintained at a nearly constant level by means of an overflow. A variation in head of one-hundredth of a foot with the average head of 1.92 feet would change the discharge by 3/10 of one per cent only.

The hook-gages used for measuring the depth of the water were held in four metal frames placed equidistant along the flume, and at right-angles to the direction of flow. Three gages were placed in each frame. With threads as cut on the shaft, the hook moved 1/16 of an inch for each revolution. To measure depth more accurately the fraction of revolution of the shaft as indicated by the head was observed.

In the preliminary operation of the flume it was evident that the overflow at the discharge-end caused a depression of the water-surface which at times extended upstream to the lower set of hook-gages. By placing small sheets of metal along the overflow, the area of overflow was decreased until the depression of the water-surface was insignificant.

A uniform layer of Palouse silt-loam soil (from same stock as that used in previously reported experiments on infiltration) was placed and carefully levelled off so that the depth of water flowing over the surface would be uniform. A number of irrigations were made to settle the soil and small quantities of soil were applied between irrigations to level up the surface.

Before each set of observations, the flume was irrigated for several hours to bring the surface to a definite condition which could be duplicated at future periods.

Observations were made as follows: The flume was placed at the desired slope by manipulation of the jack-screws, checking the elevations with a Dumpy level. The elevation of the soil-

surface at each hook-gage was obtained, and then the desired quantity of water was caused to flow over the soil by regulation of the orifices. The overflow was adjusted so that the drawdown was negligible. Then with all conditions adjusted observations were made to obtain the depth of water. The procedure was repeated with adjustments until a series of readings was obtained in which the depths checked very closely with each other.

A total of 81 satisfactory sets of observations was made. Table 1 gives the essential data.

Table 1--Slope, mean depth, hydraulic radius, and velocity of flow of water in thin sheets

No. of observation	Slope, S	Mean depth, D	Hydr. radius, R	Velocity, V	No. of observation	Slope, S	Mean depth, D	Hydr. radius, R	Velocity, V
		ft	ft	ft/sec			ft	ft	ft/sec
19	0.000513	0.0470	0.0448	0.213	112	0.00205	0.0251	0.0244	0.449
23	0.000513	0.0339	0.0328	0.365	115	0.00205	0.0260	0.0253	0.475
28	0.000513	0.0214	0.0209	0.169	117	0.00205	0.0273	0.0265	0.499
29	0.000513	0.0162	0.0159	0.145	120	0.00256	0.0085	0.0084	0.277
31	0.000513	0.0117	0.0115	0.108	126	0.00256	0.0130	0.0128	0.384
36	0.001026	0.0208	0.0204	0.353	130	0.00256	0.0150	0.0148	0.417
38	0.001026	0.0260	0.0254	0.384	132	0.00256	0.0156	0.0153	0.472
40	0.001026	0.0135	0.0133	0.175	137	0.00256	0.0177	0.0174	0.487
42	0.001026	0.0108	0.0107	0.117	141	0.00256	0.0202	0.0198	0.494
45	0.001538	0.0094	0.0093	0.134	143	0.00256	0.0221	0.0216	0.508
47	0.001538	0.0117	0.0110	0.212	146	0.00256	0.0227	0.0221	0.545
52	0.001026	0.0267	0.0259	0.375	148	0.00256	0.0250	0.0246	0.539
55	0.001026	0.0313	0.0303	0.396	150	0.00256	0.0267	0.0260	0.562
61	0.001538	0.0174	0.0171	0.286	152	0.00307	0.0126	0.0124	0.397
64	0.001538	0.0190	0.0186	0.329	157	0.00307	0.0082	0.0081	0.287
65	0.001538	0.0205	0.0201	0.359	159	0.00307	0.0060	0.00596	0.210
69	0.001538	0.0247	0.0241	0.405	161	0.00307	0.0110	0.0109	0.329
71	0.001538	0.0273	0.0265	0.413	163	0.00307	0.0147	0.0145	0.427
73	0.001538	0.0281	0.0273	0.440	165	0.00307	0.0166	0.0163	0.444
75	0.001538	0.0122	0.0121	0.193	169	0.00307	0.0185	0.0182	0.467
78	0.001538	0.0284	0.0276	0.435	171	0.00307	0.0200	0.0196	0.500
80	0.001538	0.0300	0.0281	0.454	173	0.00307	0.0217	0.0212	0.519
81	0.001538	0.0317	0.0306	0.473	175	0.00307	0.0230	0.0225	0.537
85	0.001538	0.0352	0.0339	0.493	177	0.00307	0.0244	0.0238	0.558
88	0.00205	0.0156	0.0153	0.320	180	0.00359	0.0061	0.0061	0.207
91	0.00205	0.0111	0.0110	0.212	183	0.00359	0.0078	0.0077	0.303
94	0.00205	0.0078	0.0077	0.162	186	0.00359	0.0104	0.0103	0.347
98	0.00205	0.0169	0.0167	0.371	187	0.00359	0.0117	0.0115	0.427
99	0.00205	0.0182	0.0178	0.406	190	0.00359	0.0132	0.0130	0.473
104	0.00205	0.0208	0.0205	0.415	192	0.00359	0.0162	0.0159	0.454
108	0.00205	0.0227	0.0221	0.441					

The method used in calculating the values of the exponent M was to plot R and V for groups of observations having equal or nearly equal values of S on logarithmic paper. It was found that straight lines could be fitted which reasonably well represented the data. Measurement of the slopes of these lines gave values of M for each group. The average value of M, weighted in accordance with the number of points represented by each line, was then determined. The data were then collected in groups of observations having equal or nearly equal values of R and the exponent N found in the same way. By this method weighted mean values of 0.86 for M and 0.74 for N were found. The spread of the data was such as not to appear to justify values to two significant figures and the values 0.9 for M and 0.7 for N are proposed.

The value of K was then determined by substituting these latter values for M and N in the formula and solving for K for each set of observational data. The average value of K was found to be 1100. The general formula may then be written

$$V = 1100\, R^{0.9} S^{0.7}$$

With water flowing in thin sheets the width is very large compared with the depth, and the hydraulic radius approaches the depth. For example, if the width is 100 times the depth, R = 0.98D and the formula would become $V = 1080\, D^{0.9} S^{0.7}$.

There is a definite tendency for N to decrease with increase in R, but slight, if any, indication that M decreases with increase in S. The data are not sufficient to make any reliable estimates of the changes, if any, in the values of K, M, and N with changes in V. There seems to be some tendency for M to decrease with increase in V, but no relation is evident between the values of K or N with V.

The tendencies for N to decrease with increased values of R and for M to decrease with increased values of V are probably associated with the degree of turbulence of flow as discussed heretofore by Horton (Trans. Amer. Geophys. Union, 15th annual meeting, pp. 393-404, 1934) and others.

It is obvious that the formula suggested herein is of limited applicability and that much more work must be done before a general formula covering the flow of water in thin sheets can be devised.

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OUTLINE OF THE ENERGETICS OF STREAM-TRANSPORTATION OF SOLIDS

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Introduction

The value of the theorems of energy in dealing with problems in the mechanics of real fluids is well known. The failure of energetic analysis to yield the equations of motion does not preclude the achievement of useful results through its application to those problems for which such equations cannot be obtained; and in this category may be placed most problems of consequence in fluid mechanics. The theorems of energy are useful in dealing with such problems because all internal motions and forces may be disregarded and only the energy-changes of the whole system considered. In other words, only the boundary-conditions need be known.

The purpose of this paper is to indicate a line of attack on the problem of stream-transportation of solids through consideration of energy-relations. The treatment is brief and necessarily superficial in many respects. However, it is felt that this analysis will (a) show the real nature of the various difficult problems involved, (b) indicate possible methods of solution, and (c) afford a rational basis for the systematic interpretation of experimental results.

The energy of flowing water

A stream does work through the expenditure of energy by the flowing water. In this paper only mechanical energy will be considered.

Following a convenient and familiar plan, the energy of the flowing water is expressed as

$$E = H + \alpha V^2/2g \qquad (1)$$

where E = average energy-content of each unit-weight of fluid passing any particular cross-section, H = vertical distance of water-surface above any chosen datum-plane, V = the mean velocity of flow through the cross-section, and α = a coefficient to correct for the variation over the cross-section of the average local velocities. In the equation each term represents a length or "head." H is a measure of potential energy and $\alpha V^2/2g$ of kinetic energy.

Equation (1) is strictly correct only for flow in which (a) the pressure-distribution in a vertical is the same as for still water, and (b) the flow is of a stream-line or laminar nature, and not turbulent.

When, due to curvature of stream-lines or to converging or diverging flow, vertical acceleration of the particles occurs, the pressure-distribution is not the same as for a static fluid. Strictly speaking then, flow would have to occur in parallel stream-lines to satisfy condition (a). While flow in natural streams is never perfectly uniform and rectilinear, ordinarily departures from uniform flow are not so abrupt as to cause measurable deviation from a static pressure-distribution. This statement holds for both stream-line and turbulent flow. It should be kept in mind, however, that where appreciable vertical acceleration takes place non-static pressures will exist within the fluid and equation (1) may be in error. Especially in model-work is there danger of errors from this source.

Referring to condition (b), it may be remarked that practically all stream-flow is turbulent in character, that is, eddies, or vortices, are formed within the fluid. The motion of the particles is whirling and pulsating and along unordered paths. It is clear that for this state of motion kinetic energy is possessed by the particles due to their movements in directions other than that of the mean velocity, and that this kinetic energy is not taken into account by the term $\alpha V^2/2g$. This additional kinetic energy is sometimes called the "energy of turbulence." Its existence may be indicated by adding another term to equation (1), thus

$$E = H + \alpha V^2/2g + T \qquad (2)$$

where T represents the average amount of turbulent energy contained in each unit-weight of flow. The limitation of (2) with respect to pressure-distribution is the same as for laminar flow.

Expenditure of energy

In connection with transportation of débris the important factor is the rate of expenditure of the energy of the flowing water. More specifically, it is that portion of the expended energy that is available to do the work of transportation which is of especial interest.

Energy-expenditure per unit-weight of fluid--The average rate at which energy is being lost by each unit-weight of fluid at any section of the channel may be found by differentiating equation (2) with respect to length L (measured positive downstream). This process yields

$$\partial E/\partial L = \partial H/\partial L + \partial(\alpha V^2/2g)/\partial L + \partial T/\partial L \qquad (3)$$

Here $\partial E/\partial L$ represents the slope of the so-called energy grade-line and $\partial H/\partial L$ the slope of the water-surface. Designating these quantities by S_e and S, respectively, equation (3) may be rewritten

$$S_e = S + \partial(\alpha V^2/2g)/\partial L + \partial T/\partial L \qquad (4)$$

If the flow is strictly uniform, then the last two terms in (4) vanish and $S_e = S$. For non-uniform flow these terms tend to annul each other, since T will, in general, increase with a decrease in V and vice versa. Under ordinary circumstances, however, $\partial T/\partial L$ is relatively small. It is clear then that for velocity increasing downstream S_e will be less than S, while for decreasing velocity S_e will exceed S.

The energy grade-line is usually defined as an imaginary line located a vertical distance equal to $\alpha V^2/2g$ above the water-surface. This definition neglects the energy of turbulence, T. While T, for ordinary degrees of turbulence, constitutes but a small fraction of the total energy, there appear to be situations in which it plays an important role. For example, there is considerable evidence that turbulent energy may be "regained" if, by some device, the turbulence may be reduced. If this is true, it provides a reasonable explanation for the occurrence of venturi-meter coefficients greater than one, as well as for a number of other unexplained hydraulic phenomena.

At the relatively high velocities and slight depths sometimes used in movable bed laboratory-models the existence of sand-waves might conceivably cause a rapid fluctuation in T as the water passes downstream and thus bring about conditions quite dissimilar to those in nature.

Total energy-expenditure--The rate of expenditure of energy of the whole stream may be expressed by the equation

$$P = wQS_e \qquad (5)$$

where w is the weight of a unit-volume of the fluid and Q is the volume-rate of flow. P represents the energy-dissipation in a unit-length of channel per unit of time, that is, P is the power generated by dissipative forces in each unit-length of channel. When the flow is uniform, $S_e = S$ and

$$P = wQS \qquad (6)$$

It seems logical to expect some relation between the rate of energy-expenditure and the débris-carrying capacity of a stream. This idea was early developed by J. A. Seddon (J. Ass. Eng. Soc., v. 5, pp. 127-134, 1886) who wrote the equality

$$QS = f(\text{cross-section})$$

where f indicates "function of." G. K. Gilbert (U. S. Geol. Surv. Prof. Paper 86, 1914) attempted to refer transportation of débris to total energy-expenditure by studying that quantity which he defined as the efficiency of the stream--the transportation-capacity divided by the quantity QS. More recently C. H. MacDougall (Trans. Amer. Geophys. Union, 14th annual meeting, pp. 491-495, 1933) has proposed an equation relating rate of bed-load movement with the variables QS and S.

The principal difficulty in correlating débris-transportation capacity with energy-expenditure arises from the fact that the energy expended in transporting solids is but a portion of the total energy expended--has, in fact, something of the nature of a residual quantity. The proportion of the energy-expenditure available for débris-transportation at any point in the stream depends upon (a) the other demands upon the total energy-expenditure at that point and (b) the relative ability of the various coexistent demands to command the available energy under the given conditions.

The next step is to examine the nature of the various demands that may be made upon the total energy expended by the stream. It will be noted that the term demand is here used to denote a rate.

Energy-demands

The energy expended by a stream may be used in any or all of several different ways, the chief of which are:

(1) In overcoming resistance due to purely viscous shearing forces as in laminar flow
(2) In creating and maintaining turbulence in the fluid
(3) In transporting solids
(4) In doing work in the alteration of the channel-section
(5) In creating and maintaining waves on the surface of the stream
(6) In creating and maintaining bed-waves (sand-ripples)

Demands 1 and 2--In turbulent flow--with which this paper will deal exclusively from this point on--the rate of energy-dissipation by turbulence is so great compared to losses due to viscous shear that the latter may, in general, be disregarded. As an illustration of the relative magnitudes of the two losses, a stream 14 feet deep flowing turbulently with a mean velocity of 5 feet per second will, even in the smoothest of channels, dissipate energy at a rate about 1000 times greater than would be the case if the flow could be laminar. Actually, of course, it would be impossible for laminar flow to occur at the given depth and velocity.

It is clear then that losses to viscous resistance are negligible in ordinary natural streams. This may not be true in some models or in natural streams of extremely low velocity. The latter, however, do not carry débris.

Demand 3--In the foregoing outline, the energy required to transport both suspended material and bed-load are lumped under one head. It is convenient, however, to distinguish between the two, for although the two loads merge into each other near the bed there are fundamental differences in the mechanisms of transportation for the two.

The transportation of suspended load constitutes an energy-demand because the particles must be continuously thrown back into suspension as they settle, or tend to settle, out. The turbulence of the fluid is the mechanism by which the particles are kept in suspension.

The movement of particles near the bed, while it may be partially a function of turbulence, occurs through the operation of another type of mechanism--the forces brought about by the impingement on bed-particles of the flowing water in and near the boundary-layer. Since the velocity close to the bed is not a function of turbulence alone, it is necessary to distinguish between the work done by the two modes of transportation.

Demand 4--Another distinction must be made between the energy-expenditure required to simply move débris through a reach at a steady rate (débris-inflow = débris-outflow) and that additional energy required to change the channel-section in the reach. There is, to be specific, a fundamental difference between the demands for transportation and for scour.

Demand 5--The energy-demand of surface-waves is practically negligible, relative to total expenditure, for large streams flowing at ordinary velocities. In model-work, however, it may constitute a large enough proportion of the total energy-expenditure to seriously impair experimental results.

Even when the energy-demand for maintenance of the surface-waves is negligible, the demand during formation of the waves may be high. For example, assume that a wave-pattern starts to form on the surface of a stream initially smooth. The pattern will come into existence quickly and its creation may bring about a fairly heavy drain of a transient nature on the available energy-supply. This will cause the flow to become unsteady, since the slope of the surface in the reach will increase, and during this process flow will be impounded.

Demand 6--The formation of ripples or sand-waves on the bed of the stream affects the energy-expenditure in two ways:

(a) The average amount of turbulence may be increased by the waviness of the bed, regardless of any bed-movement. This may be thought of as an effect of increased hydraulic roughness.
(b) In much the same way as for surface-waves, energy is required to produce and maintain the bed-waves. This energy-expenditure is analogous to that caused by waves at the common surface of two fluids of different densities.

Just as for surface-waves, there is a larger demand for energy during the period of formation of the bed-waves and this results in unsteady flow.

The above discussion on the energy-demands of waves is included here largely because of its importance in interpreting the results of the type of model-experiments now in vogue. In a true model the energy-demands of waves would bear the same ratio to the total energy-expenditure as in the prototype. Unfortunately this is never the case in laboratory-experimentation.

Formulation--To give the foregoing ideas a concrete and usable form, the various energy-demands may be expressed as slope-factors similar to the term S_e. These factors represent the demands on the average energy-content of the unit-weights of fluid as they traverse a unit-length of channel. The following notation is used: S_v = energy-expenditure to viscous shear; S_t = energy-expenditure to turbulence; S_s = energy-expenditure to transportation of suspended material; S_g = energy-expenditure to transportation of bed-load; S_c = energy-expenditure to work on channel; S_w = energy-expenditure to surface-waves; and S_r = energy-expenditure to bed-ripples.

Since the total expenditure of energy is given by S_e, it is obvious that

$$S_e = S_v + S_t + S_s + S_g + S_c + S_w + S_r \qquad (7)$$

In this expression S_e has been broken down into such component parts as are convenient for present purposes. In particular cases some of the factors may be set equal to zero and others may be combined into one.

It is now apparent that the total energy expended must be divided up among a number of demands. For example, the rate of energy-dissipation in turbulence is given by $P_t = wQS_t$, that demanded by the suspended load by $P_s = wQS_s$, etc.

The first major problem in the study of débris-transportation is thus revealed. It may be stated as follows: To determine for all possible sets of conditions the division, among the various demands, of the total energy expended.

Priority of demand--Assuming a given rate of energy-expenditure at any section of a stream it is clear that, should one, or a certain few, demands be capable of appropriating all of the available energy, then nothing would be left to the other possible demands. This leads to the idea of priority of demand. If a certain store of energy is available, the various demands present compete for it and those having priority, or preference, must be satisfied, up to a certain point, before energy is available to other demands. For example, in turbulent flow the demand of turbulence is probably always preeminent, but when the expenditure of energy in turbulence reaches a certain stage, any increase in available energy will be divided between increased turbulence and other demands. Again, when the available energy is excessive because of the steepness of the channel, all of the ordinary demands approach a state of full satisfaction. When this occurs, excessive waves come into being. This is only another way of saying that nature will seek in extreme cases the more unusual means of bringing about equilibrium-conditions. In fact, if they are required, unusual energy-demands not mentioned before may be brought into play. For example, in very steep flumes admixture of air and water will take place.

The conditions under which certain demands have priority is not a problem admitting of solution by energetic analysis. Priority is a function of the internal motions of the fluid, the character of débris carried, the material of the bed, etc. Any knowledge thereof must be

sought in dynamic analysis or in experimental investigation. At the present time the latter appears the only feasible method of approach to a solution.

The foregoing leads to the statement of the second major problem of the present subject: To determine the order of priority of the various demands under different possible sets of conditions and to find out the effect on any demand of the operation of other coexistent demands.

Forces exerted

The dissipation of energy by a stream comes about through the work done by innumerable small dissipative forces acting in all directions throughout the fluid and at the boundaries. As before stated, energetic analysis takes no cognizance of these internal forces and thus far it has been found impossible to investigate them by the rigorous methods of analytical dynamics. Calculation of a resultant for all these forces is out of the question.

If the rate of energy-expenditure P is known it is, of course, possible to calculate a fictitious "equivalent" force which, moving at the velocity V, would generate the power P. It would not be expected that any particular physical meaning could be attached to this force, but this should not entirely preclude its being useful. Let this equivalent force be denoted by F. Then $P = FV$ and

$$F = P/V = wQS_e/V = wAS_e \tag{8}$$

where A denotes the cross-sectional area of the stream. For uniform flow $S_e = S$ and

$$F = wAS \tag{9}$$

Again, for a unit-width of stream A = depth and

$$F = wDS \tag{10}$$

where D represents depth of fluid. The value of F calculated from (10) constitutes the so-called DuBoys "tractive force."

It is important that the true nature of F be kept in mind. To repeat, F is that fictitious equivalent force which, moving at the velocity V, would generate the power P. Further, it should be noted that equation (10) is based upon uniform flow in a channel of unit-width. In general, (10) is not equivalent to equation (8).

Equation (10) is usually derived by calculating the forces acting on a solidified prism of fluid, occupying a unit-width of a very wide channel, and sliding down a sloping bed at a uniform velocity. This manner of derivation has led some to believe that F, computed from equation (10), represents the actual shearing force exerted on the bed of a stream. But the foregoing derivation of F from energetic considerations shows the utter falseness of this point of view and reveals the true nature of this fictitious "force."

The matter may be pursued one step farther before leaving the subject. Equation (8) may be rewritten by substituting the relation of equation (7) (neglecting the term S_v therein), thus

$$F = wA(S_t + S_s + S_g + S_c + S_w + S_r) \tag{11}$$

The DuBoys expression is sometimes said to represent the resultant force exerted in the movement of bed-load. It is easy to see from (11), however, that the equivalent force exerted in bed-load movement constitutes but a fraction of the force F, and that this fraction may be represented by

$$F_g = wAS_g \tag{12}$$

when the channel-section is stable and bed-load movement steady. When scour is taking place, the equivalent force acting on bed and banks is given by

$$F_{g+c} = wA(S_g + S_c) \tag{13}$$

There is no evident reason for attempting to correlate débris-movement with F rather than directly with P. As was before stated, Gilbert used the latter scheme and MacDougall has repaired to it. The use of P appears more rational in view of the fictitious nature of F, but the difficulties met in finding a satisfactory relation seem to be just as great in either case.

The obvious quantity with which to correlate débris-movement is that portion of the total power used in moving the débris. Thus, in certain cases, bed-load movement will be closely correlated with P_g, although apparently having no relation to P. The real problem, then, is to separate S_g from S_e. This is merely a restatement of the "first major problem."

Application of ideas outlined

The practical value of the ideas so far developed is not entirely self-evident. Therefore, it seems necessary to indicate how these concepts may be made to serve useful ends.

Applications to experiment--It appears that, for the present at least, the value of the formulation resides in its utility as a basis for the interpretation of experimental data. In experiment and especially in hydraulic-laboratory investigations enough measurements may be obtained to closely determine S_e through equation (4). Given S_e, the problem reduces to: (a) Breaking down S_e into its component demands and relating these to measurable characteristics of flow, channel, bed-material, débris-load, etc.; (b) establishing correlations between transporting capacity and the energy supplied to transportation-demands.

The evaluation of demands does not come within the scope of this paper. However, to indicate the general procedure that would probably be followed in experimental evaluation, a few of the simpler problems of bed-load movement will be briefly considered.

Problem A--Consider a stream of clear water in uniform flow moving bed-material without the formation of bed- or surface-waves. Assume that the bed is stable so that bed-load is leaving any reach at the same rate as it enters. Under the prescribed conditions

$$S_e = S = S_t + S_g \text{ or } S_g = S - S_t$$

and

$$P_g = wQ(S - S_t) \tag{14}$$

In this very special case S_t may be approximately evaluated through use of an empirical formula such as that of Manning. According to this formula

$$S_t = n^2V^2/2.21\,R^{4/3} \tag{15}$$

where n = a coefficient of roughness and R = hydraulic radius. To estimate a proper value of n, the results of experiments on fixed bed-channels of the same roughness and about the same size and shape are required. In calculating S_t it would seem reasonable to use a value of V equal to the difference between the velocity of the water and that of the bed-load.

Parenthetically it may be stated that S_t is the proper value of the slope-factor for use in any formula of the Chezy type (such as those of Manning, Kutter, etc.). If the value of S_e is used when demands other than S_t are in operation, then it is clear that such formulas are being used to cover energy-losses of a kind not considered in their derivation. The value of "n" could not be the same for two like streams flowing in channels of equal roughness if one transported débris and the other did not.

For exact results in laboratory-work S_t could be determined experimentally by determining S_e for a fixed-bed model of precisely the same roughness as the movable-bed model. For this case $S_e = S_t$.

Having determined S_t the value of S_g is made available and P_g may be computed from (14) using the value of w for clear water. For a given bed-load material it would seem that the rate of movement should be a fairly consistent function of P_g.

Problem B--The problem may be complicated by assuming the same stream to be carrying a suspended load. Then

$$\left.\begin{aligned} S_e &= S = S_t + S_g + S_s \\ S_g &= S - (S_t + S_s) \\ P_g &= wQ(S - S_t - S_s) \end{aligned}\right\} \tag{16}$$

It is easy to see that for a given S the value of S_g must be less when the water contains suspended material than when it is clear.

Despite the decrease that occurs in S_g (for a given S) it does not necessarily follow that P_g will be decreased, since w is increased by the suspended load and this tends to increase the total energy-expenditure P. For specified values of Q and S, then, the question arises: For any given channel and concentration of load, what is the combined effect on P_g of the increase in w and the decrease in S_g? For concentrations of suspended material of ordinary magnitude, experiment seems to indicate that P_g becomes smaller. This does not preclude the possibility of occurrence of the opposite action under suitable, even if unusual, circumstances.

In the above Q and S were assumed fixed. It is easier to analyze the situation when P and S are fixed, that is, when the mass-rate of flow is held constant in a given channel. For this condition there can be no doubt that the rate of bed-load movement would be less for muddy than it would be for clear water expending energy at the same rate P. Another way of putting the matter is to state that the ratio P_g/P will be less for muddy water than for clear water in the same channel.

S_t may be approximately evaluated by using formula (16) as before. The roughness-factor "n" should be the same as for clear water.

The effect of a suspended load is to increase the viscosity of the fluid and thus to increase the value of S_v; which demand has been heretofore neglected. It is conceivable that S_v may, in unusual cases, be increased so much that its neglect may not be justified. Although dependable formulas for flow in smooth pipes have been developed in which the viscous resistances are taken into account--for instance, C. H. Lander's formula (Proc. R. Soc., A, v. 92, pp. 337-353, 1916)--no reliable formula for open channels is available.

In laboratory-work ($S_t + S_s$)--or ($S_v + S_t + S_s$) when S_v is appreciable--may be determined by passing the muddy water over a fixed bed of the required roughness. The difference between the values of S_e for the movable and fixed beds is the value of S_g.

Problem C--Next consider the problem of bed-load movement for uniform flow, uniform bed-load flow, no suspended load, surface- and bed-waves in existence. Proceeding as before

$$S_e = S = (S_t + S_g + S_w + S_r)$$

$$S_g = S - (S_t + S_w + S_s) \qquad (17)$$

$$P_g = wQ(S - S_t - S_w - S_r)$$

The above immediately indicates that P_g is decreased by the presence of the wave-demands.

Any attempt to evaluate S_t in the above leads to considerable difficulty, since the bed-ripples have increased the value of "n" by an unknown amount.

It is possible, however, to get at the sum of the demands ($S_t + S_w$) experimentally when dealing with small laboratory-channels. To do this a cast may be made of the stabilized bed-ripples formed during any test. By reproducing these ripples as a fixed bed, tests may be run which will yield the combined demand ($S_t + S_w$).

The evaluation of S_r promises to be difficult. While this loss may be small, it does not seem possible to prove it so without a rather extended experimental investigation.

The examples outlined are the simplest obtainable. The really difficult problems are those involving bed-changes (S_c not equal to zero), those for the unsteady conditions existing when the demands are variable, and those involving non-uniform flow.

Consideration of the above examples gives a hint of the complexity of the relations between the various demands. It is impossible to change any one demand without affecting all others present. For instance, in a stream carrying bed-load, S_t may not be increased to a point at which S_g will become zero, for changes in S_t induce changes in the internal motions which, in turn, inhibit further reductions of S_g. The law of Le Chatelier governs all such changes, but yields no information of practical value.

General applications--Until the various energy-demands have been fairly well investigated, there is little possibility of using the energy-equations to predict the behavior of artificial channels or to apply this line of reasoning to investigations in the morphology of streams.

No general conclusions can be drawn from the formulation here presented except the following, which is self-evident: A stream cross-section tends to assume a form which will allow the total energy-expenditure to be dissipated without work being done in altering the section, that is, S_c will normally tend toward zero so that all of the available energy may be demanded by S_t, S_g, and S_s. This conclusion is too general to be of any particular aid.

W. W. Rubey (Trans. Amer. Geophys. Union, 14th annual meeting, pp. 497-505, 1933) has made a very interesting application of energetic analysis to the problem of equilibrium-conditions in streams. He developed an expression equivalent to the following:

$$S_e = S = S_v + S_t + S_s$$

He then evaluated $(S_v + S_t)$ by use of a common formula for the "frictional" loss of flowing water. He also attempted to evaluate S_s but this problem appears to be more complex than his treatment indicates.

Conclusion

This paper has attempted to delineate a general line of reasoning more or less applicable to all of the special problems of débris-transportation. The preceding outline should not be considered, in itself, a solution of these problems. It would be more correct to call it a restatement of the general problem of stream-transportation. It is hoped that this restatement will clarify an obscure subject and aid investigations in the field.

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SOME OBSERVATIONS OF SORTING OF RIVER-SEDIMENTS

Lorenz G. Straub

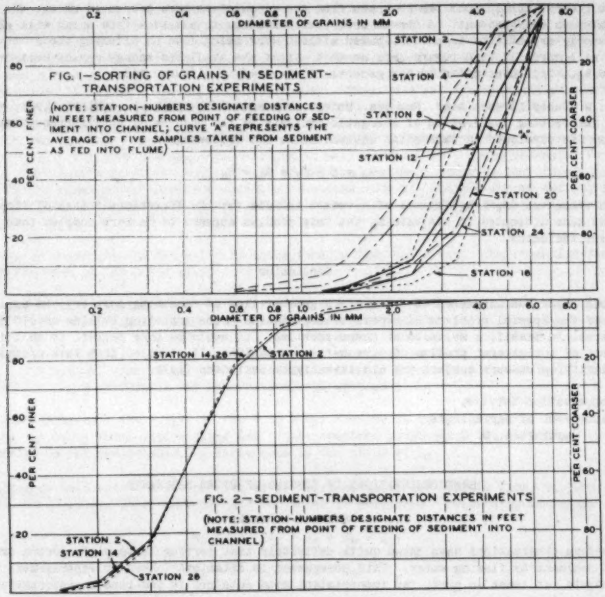
Various observations have shown quite definitely that sorting takes place during transportation of sediment by flowing water. This phenomenon is often overlooked in experimental studies, and accounts, at least in part, for inconsistent data obtained in bed-load transportation experiments.

Laboratory-studies

The writer observed the results of this sorting process on the Missouri River on various occasions when the sedimentary characteristics of the River were being investigated, and also in the course of sediment-transportation studies in the hydraulics laboratory at the University of Minnesota. The laboratory experimental work was carried on using materials of various mechanical compositions. In one case, the material, a fine gravel, was as uniform in size as one might expect to obtain commercially. No sorting was to be expected. It was the material retained on a No. 8 sieve and passing a No. 4, resulting in an average size of grain (according to mechanical analysis) of 4 mm (Fig. 1). The material was fed into the headwater end of a flume at such a rate as to maintain the slope constant; it was collected at the downstream end of the flume and weighed periodically. A progressive change in the rate of sediment-discharge, at least for a time, was observed, although all conditions were maintained as nearly constant as practicable. That this change was, at least in part, due to sorting was evident from subsequent studies. A typical example is shown by Figure 1.

The experiment was performed in a flume one foot wide and about 30 feet long. The sediment was originally placed in the flume at a slope of 1.5 per cent, and the discharge of water was set at 0.50 cubic foot per second. Sedimentary material was added uniformly at the upstream-end of the flume, and the elevation of the downstream-end was raised by putting half-inch sills at the point of discharge at intervals of 12 minutes. The rate of feeding sedimentary material was slightly greater than for an equilibrium-condition for a 1.5 per cent slope, the slope gradually increasing to 2.1 per cent. At the end of the run, specimens were gathered from the stream-bed at distances of 2, 4, 8, 12, 16, 20, and 24 feet measured from the initial point at which the sediment was fed in. Care was taken to obtain representative samples which were mixed and quartered before being analyzed.

It will be observed that in this case (contrary to the usual conception) the coarser material was being transported more rapidly than the finer, the latter being predominantly present



near the headwater-end of the flume. A surprisingly uniform gradation took place from one end of the flume to the other, despite the fact that the original material was of quite uniform size particles.

Similar occurrences have been observed with material of finer mechanical composition. Depending apparently upon the flow-conditions and the type of material, segregation upon deposition may take place either from fine to coarse (from one end of the channel to the other), or the reverse. Much additional study is required before any definite conclusions can be drawn as to the laws governing this occurrence.

The maintenance of uniformity of mechanical composition throughout the channel requires that no aggradation takes place in the course of the experiment, but preferably that there be a slight amount of degradation, so that little of the material added at the headwater-end is deposited in travelling through the flume. With a control of this character, much greater consistency in the results was obtained. Figure 2 indicates the uniformity in the mechanical composition of a typical river-sediment when this control (slight amount of degradation) was followed. The specimens were gathered from the surface of the bed to a depth not exceeding about one-quarter of an inch.

Close examination of the surface of the bed reveals that even here a slight amount of sorting takes place, though very much localized; there is some evidence of different mechanical composition of the material at the crest and valley of the sand-riffles.

Field-investigations

Apparently the bed of a river has its sediment distributed according to a quite definite plan. To be sure, there is little known about the laws that govern this plan, but it is frequently believed that the mechanical composition of the bed is simply a heterogeneous grouping occurring merely by chance.

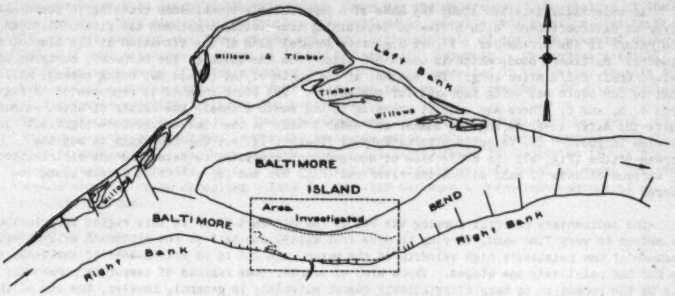


FIG. 3—MISSOURI RIVER AT BALTIMORE BEND, 1929-30

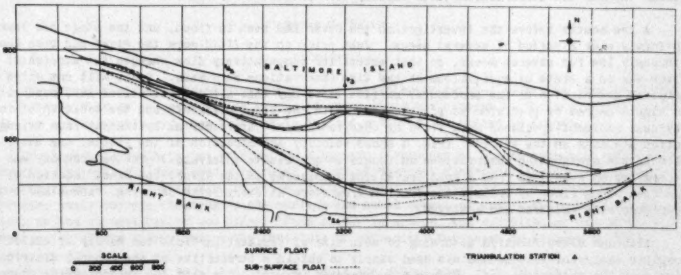


FIG. 4—VELOCITY-OBSERVATIONS

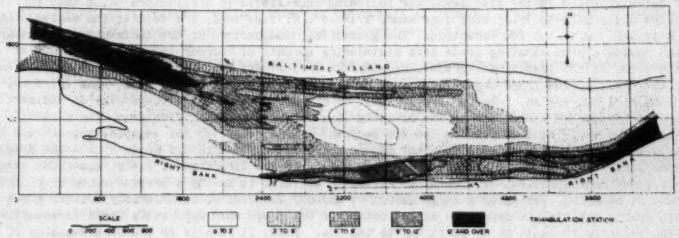


FIG. 5—SOUNDINGS

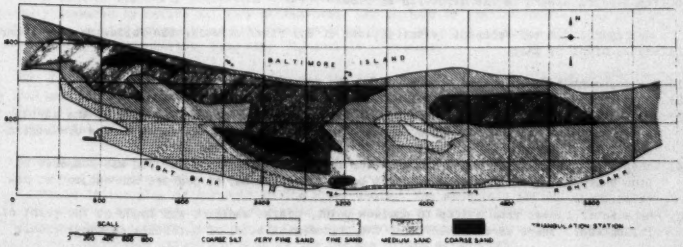


FIG. 6—BED-SEDIMENT DISTRIBUTION

An especially detailed study was made of a particularly troublesome crossing in the Missouri River at Baltimore Bend, with a view to determining some relation between the flow-conditions and the nature of the stream-bed. Figure 3 gives a general plan of the situation at the time of the studies. Baltimore Bend, which is about 300 miles from the mouth of the Missouri, contains an island about 2-1/2 miles long. The channel at the north of the island was being closed, while that to the south was being improved for navigation. The south channel is represented by Figures 4, 5, and 6. There was a split crossing in the south channel, the center of which extended above the water-level during the summer low-water season at the time of the investigation. The studies included: (a) Velocity-observations by floats (Fig. 4); (b) soundings to map the stream-bottom (Fig. 5); (c) collection of bed-sediment specimens to determine the distribution of various classes of sand within the river-bed (Fig. 6); and (d) a line of levels along the shore.

The sedimentary material forming the bed of the Missouri River in this region is principally medium to very fine sand, varying in size from mainly one-half to one-sixteenth millimeter. Because of the relatively high velocity of the water, the bed is in motion most of the time, even for the relatively low stages. There are, of course, some regions of temporary permanence due to the formation of bars of relatively coarse material; in general, however, the bed of the stream changes its conformation quite rapidly for variations in flow-conditions.

A few months before the investigation the River had been in flood, and the stage had lowered uniformly over a period of several weeks. Just prior to the field-work the River had been continuously low for several weeks, so that except for comparatively slow changes the stretch of River was in a state of equilibrium at the time observations were made. Space will not allow a detailed description of the procedure; suffice it to say that all determinations were made with as high a degree of precision as practicable. Both the float-movements and the location of individual sediment-specimens were fixed by observations of intersections by transit from triangulation-stations on the shores. (Fig. 4 shows velocity and direction of the floats, the encircled points designating observations on floats at one-minute intervals.) The bed-contour was determined by soundings from a boat travelling transverse to the River, the exact location of the boat being fixed by transit-observation from shore at every fifth sounding. About 200 bed-specimens were gathered and analyzed.

Although classification according to mean size of sediment-particle can hardly be called a complete analysis, this method was used simply to obtain a perspective of the general distribution over the area concerned. Figure 6 is prepared in accordance with the predominating grades of material found in the specimens, the following size-limits in millimeters being adopted: Coarse silt, 1/32 to 1/16; very fine sand, 1/16 to 1/8; fine sand, 1/8 to 1/4; and medium sand, 1/4 to 1/2. With but few exceptions, the geometrical composition of the sediments was similar, each having a predominating grade with diminishing amounts of coarser and finer sediments at both sides of the predominant grade. Usually the predominant grade was about 70 to 90 per cent of the total. (The grade-separations were designated by a geometrical series, that is, 1 mm, 1/2 mm, 1/4 mm, 1/8 mm, 1/16 mm, etc.) Thus, of course, in case the average size of sediment happens to come at approximately the dividing line between two classifications, the size-limitations would be taken within the two sediment-grades; that is, for example, between 1/2 mm and 1 mm, the preponderance of material may be approximately 1/4 to 3/4 mm in size. The exceptions occurred at points where the bed sloped upward in the direction of the stream-flow; at such points sediment-specimens were obtained which, in addition to having a preponderance of a certain grade of material, possessed a large amount of another material of considerably coarser grade. This coarse material is deposited at the bottom of the slope when apparently there is insufficient velocity to cause it to be raised to the top. Thus, it remains on the upstream-side of an incline sloping upward in the direction of flow.

As regards the bed-sediment investigations of the river stretch, the following very general statements might be made:

(1) The coarsest sediments were upstream from the crossing.
(2) The largest grains were found in locations of higher bottom-velocities.
(3) Where helical currents were observed, the finer materials were at the side of the current which was directed upward. This condition was particularly noticeable at the downstream-end of the longitudinal bar which splits the crossing into two parts.
(4) Except for the space of the transverse bar forming the crossing, the bed was composed of fine sediment at shallow points. This part of the stream, of course, was subject to low velocities.
(5) Where water flowed from a deep to shallow point, coarse sediment was found at the point of inflection. There were usually also two predominant sizes of materials at considerable

distance from each other on the size-scale; there was preponderance of the smaller of the two maxima. This condition was particularly noticeable opposite triangulation-station No. 4.

(6) The coarsest sediment was found on the crossing in the vicinity of the high measured velocity, and just below the crossing in the following pool. Apparently, the coarse material which had been moved from the crossing to the pool, was deposited in the latter because of the lack of adequate transporting force after the pool had been reached. This is especially noticeable opposite triangulation-station No. 2.

(7) The finest sediment was found at the downstream-end of the longitudinal sand-bar which, at the time of the observations, protruded above the water-surface. The mechanical composition of this material was very similar to that ordinarily found in suspension in the Missouri River. Apparently the flow was retarded sufficiently at this point to cause the suspended sediment to be deposited. This sediment did not have a predominant amount of a particular grade.

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DIVERSITY OF CURRENT-DIRECTION AND LOAD-DISTRIBUTION ON STREAM-BENDS

Henry M. Eakin

Introduction

The behavior of currents at stream-bends has persistently refused to retire from the field of philosophic study and speculation in the 56 years since the concept of "helical flow" was introduced independently by James Thompson in England and by M. P. DuBoys in France.

Thompson's approach to the problem was a classic forerunner of modern hydraulic-laboratory practice. He not only developed a rational theory of "helical flow" but also constructed a small-scale model of a river-bend in which the phenomenon was shown by use of seeds serving as detritus, small objects floating on the surface and small specks of anilin dye placed at selected points on the channel-bottom and sides. This model, in action, was exhibited at his original presentation of the theory before the Institute of Mechanical Engineers in Glasgow in 1879.

The same year DuBoys published his remarkable analytical memoir on "The Rhone and rivers of shifting bed" at Paris. DuBoys discussed superelevation of water-surface toward the outer banks of stream-bends and explained "helical flow" as the result of greater centrifugal force due to higher velocity in the upper part of the stream as compared with the lower.

This principle has been rediscovered from time to time during the succeeding years. I must plead guilty to having done so myself in a study of the influence of the Earth's rotation on lateral erosion of streams published in the Journal of Geology in 1910. The phenomenon has been described and explained in turn by DeFontaine, Claxton, Townsend, Moller, Schoklitsch, Straub, and others. Leighly, on the other hand, in his 1932 paper on "Stream morphology" would appear to have recognized superelevation but not "helical flow" on bends. Also Major Elliott in 1933, in his history of the Mississippi River Commission, stated that "helical flow" on certain river-bends appeared open to question; and Lieutenant Vogel, the same year, from his model-experiments at the United States Waterways Experiment Station found reason to believe that "helical flow" is absent from bends of the lower Mississippi River.

This lack of unanimity concerning a question discussed for more than half a century, and certainly answered by nature at every stream-bend, led in 1933 to special studies of current-behavior and related movement and distribution of sediment in the Mississippi River at Tamm Bend near Dyersburg and Merriwether Bend near Tiptonville, Tennessee.

The first phase of this investigation was the tracing of direction and rates of travel of pea coal and limestone-chat dumped in 500-ton lots at selected locations, one on each side of the River at each bend. It was my duty to determine the directions, distances, and approximate rates of travel of these materials by systematic dredging of samples from the river-bed.

Over a period of several weeks hundreds of dredged samples were taken and some of the material was traced downstream more than 9000 feet. The results were generally indicative but not conclusive as to the play of currents on the river-bends. The materials placed on the bar-side were not moved to any great extent but tended to be buried by accumulating sand. The materials placed on the outer concave banks of the bends were moved downstream and outward toward and, in some places, completely across the axis of the thalweg trench of the bend.

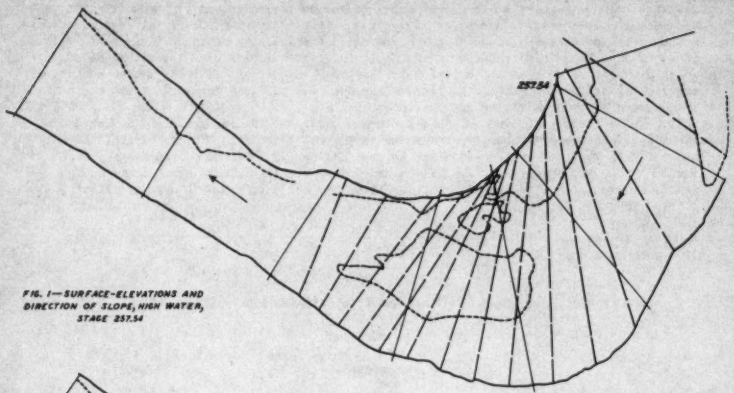

FIG. 1—SURFACE-ELEVATIONS AND DIRECTION OF SLOPE, HIGH WATER, STAGE 257.54

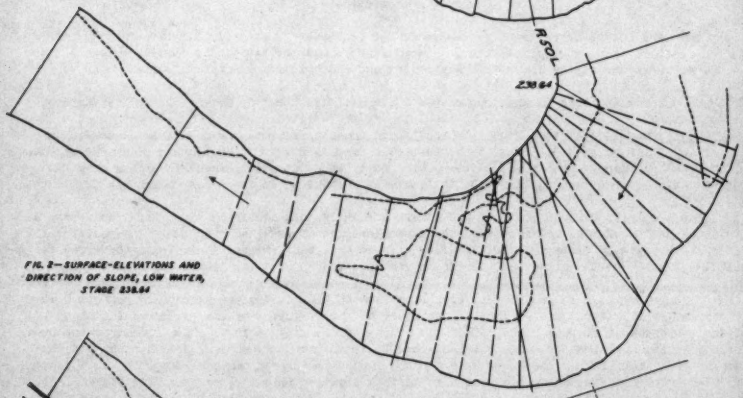

FIG. 2—SURFACE-ELEVATIONS AND DIRECTION OF SLOPE, LOW WATER, STAGE 238.64

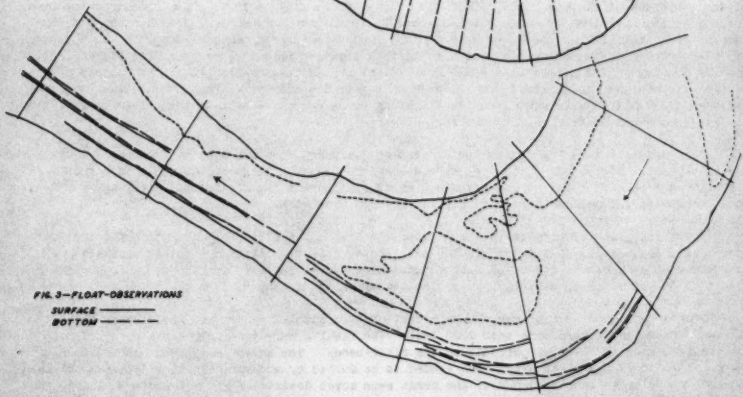

FIG. 3—FLOAT-OBSERVATIONS
SURFACE ————
BOTTOM — — —

Following the experiments with coal and chat, the investigation was broadened to include studies of surface-slope, distribution of directions and velocities of flow, the paths of bottom-currents, and the distribution of solid matter in motion and comprising the banks, bars, and channel-bottom.

Figure 1 shows the relative positions of points of equal elevation of water-surface on the two sides of the River at a rather high stage at Tamm Bend. The broken lines across the River are drawn between such points. Note that the water-surface at the concave bank in places is as much as half a foot higher than directly across the River.

Figure 2 shows the same phenomenon with the River at stage approximately 20 feet lower. Maximum superelevation has dropped to three-tenths of a foot and its position has moved about one-half mile upstream. The point of maximum superelevation and the related maxima of "helical flow" and bank-erosion were observed to shift upstream with falling stage and downstream with rising stage of the River over a distance of about five miles along the outer bank of this bend during the period of 11 months in which these studies were made.

The next test of current-behavior was made by checking the courses of surface and deep-set floats from common starting points.

Figure 3 shows the paths of the surface-floats by solid lines and deep-set floats by broken lines. Where the surface-currents follow curvilinear paths, the bottom-currents consistently curve in the same direction. Their curvature in each case, however, seems to relate to a different center located somewhat closer in and farther upstream. Where the surface-currents run straight in the outflow of the bend, the bottom-currents tend to do likewise.

The third test of current-behavior at the bend was made with a special current-direction recording apparatus developed for this project. The device consisted essentially of a mariner's compass and moving-picture camera, with electric controls and lighting, inside a ruddered watertight cylinder arranged for cable suspension in the River. Plate I-A shows the general appearance of the apparatus suspended above the water. Plate I-B shows the interior of the cylinder, with camera and diaphragm removed and compass in place. The camera was mounted solidly within the cylinder so as to rotate in focus on the compass-card and automatically record the successive azimuths of rudder-direction during periods of operation. Plate II-A shows a sample film with azimuth-records equivalent to three observations and notebook entries per second.

Current-velocities were taken with a conventional current-meter hung immediately above the direction-recorder. Also sediment-samples were taken at surface, at mid-depth, and near the bottom of the River, as also a sample of the river-bed itself.

Suspended-sediment observations were made with a special apparatus also developed for the project. This apparatus as shown in Plate II-B is arranged to trip automatically on contact with the river-bottom and take five simultaneous samples spaced evenly 1, 2, 3, 4, and 5 feet above the river-bed. The wire shown in this view is for attachment of line for hand-tripping of the apparatus at any desired depth. This manual method was used in taking mid-depth samples while surface-samples were obtained by dipping standard-volume samples from the surface of the River. Plate II-B shows the cylinders shot home and containing samples of water from near the river-bottom. Note the raised plate, loosed dogs, unflexed springs, and contact of the cylinders with the plates at their bottoms. The cylinders are held against soft-rubber gaskets on these plates which provide water-tight contacts.

The samples were recovered by placing the whole apparatus on an unloading frame arranged to hold a large funnel and receptacle beneath each sample-chamber. The samples were filtered directly and the residues folded with the filter-papers and encased in celophane-wrappers. At the laboratory the filter-papers were reduced to ash in an electric oven and the residues weighed and expressed as ppm of sediment to total sample weight of water, due correction being made for the average weight of the paper-ash involved.

Figure 4 illustrates the general method of reducing direction-, velocity-, and depth-data to terms of lateral circulation in the plane of range cross-section. The first step is derivation of the azimuth of mean direction of flow. This was computed by weighting sines and cosines of angles of departure from least azimuth for velocity and depth of water represented and taking the ratio of average weighted sines and cosines as the tangent of the mean angle of departure. Adding mean angle of departure to least azimuth of the series gives the azimuth of the vertical plane through which lateral mass-motion to right and left are balanced, in this case 77° 10'. The next step was the derivation of actual velocities of lateral movement through this plane at

PLATE I-A

PLATE I-B

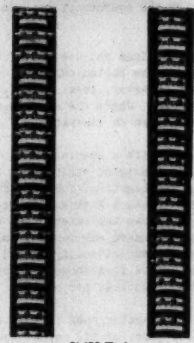

PLATE II-A

PLATE II-B

the different depths of observation. This is taken to be the product of observed velocity and sine of the angle of departure of observed direction from that of the reference-plane. These lateral velocities for this particular point of observation (Point 1, Range 50 lower, shown graphically in Fig. 5) are given in column 5 of the lower section of Figure 5.

A final operation is made necessary by the fact that the lines of balanced circulatory movement are not the same at the various points of observation along the range and generally depart from normal to the range-direction. Circulatory velocities in the plane of the range cross-section are therefore computed as the product of lateral velocities through the plane of balanced lateral movement and the cosine of the angle of departure of this plane from normal to range-direction. These results are given in column 6 of the lower table of Figure 5 and are represented graphically on the following chart of Figure 5 as the actual lateral circulatory velocities of water, in the plane of the range cross-section which is directly across the stream-channel.

Figure 5 is a graphic summary of the various data taken on a characteristic range of Tamm Bend at medium high water (Range 50 L of Fig. 1). "A" shows directions and scale-distances of motion per second for top and bottom waters and mean flow. "B" is a true-scale picture of the range cross-section. This is inserted to show the strain put on the term "helical" as commonly used to describe the play of currents disclosed in the next graph. "C" is plotted from the data of lateral velocities in the plane of the range cross-section given in column 6 of the table in Figure 5. It is to be noted that the surface-waters of the thalweg region move toward the concave bank, downward and then out across the channel-bottom toward the bar. In this particular case, bottom-currents on the margin of the bar have a lateral motion toward the concave bank giving a zone of convergency of bottom-currents and, of course, compensating upward motion of water. In a broad zone on the bar, adjacent to the convex bank, shoreward currents at the bottom and outward return-currents at the top are indicated.

Range 50 L
Point No. 1

Derivation of distribution and magnitudes of lateral motion

Depth	Azimuth	Divergence from least azimuth +	Sin	Cos	V	D	VD	Sin VD	Cos VD
Surface	71° 10'	1° 25'	.02472	.99969	3.30	5	16.5	.407880	16.494885
10	71° 42'	1° 57'	.03403	.99942	3.63	10	36.9	1.255707	36.878538
20	69° 45'	0° 00'	.00000	1.00000	3.72	10	37.2	0.000000	37.200000
30	74° 10'	4° 25'	.07701	.99703	3.62	10	36.2	2.787762	36.092486
40	73° 25'	3° 40'	.16792	.98580	3.48	10	34.8	5.843616	34.305840
50	83° 25'	13° 40'	.33655	.94167	3.04	8	24.3	8.184896	22.901414
56	93° 25'	23° 40'	.40141	.91590	2.77	7	19.4	7.789339	17.759301
60		Total					205.3	26.263200	201.632524

Mean Direction of Flow

$$\frac{\text{Total Sin VD}}{\text{Total Cos VD}} = \frac{26.263200}{201.632524} = .130253 = \text{Tan } 7°25' + 69°45' = 77°10'$$

Lateral Velocities

Depth	Angle of divergence from mean	Sin	V	Normal to mean	Normal to normal to Range (Cos .97764)
Surface	- 6° 00'	.10453	3.30	- .3449	- .3372
10	- 5° 28'	.09527	3.69	- .3515	- .3436
20	- 7° 25'	.12908	3.72	- .4801	- .4694
30	- 3° 00'	.05234	3.62	- .1894	- .1852
40	+ 2° 15'	.03926	3.48	+ .1366	+ .1336
50	+ 12° 15'	.21218	3.04	+ .6450	+ .6305
56	+ 16° 15'	.27903	2.77	+ .7751	+ .7577

FIG. 4

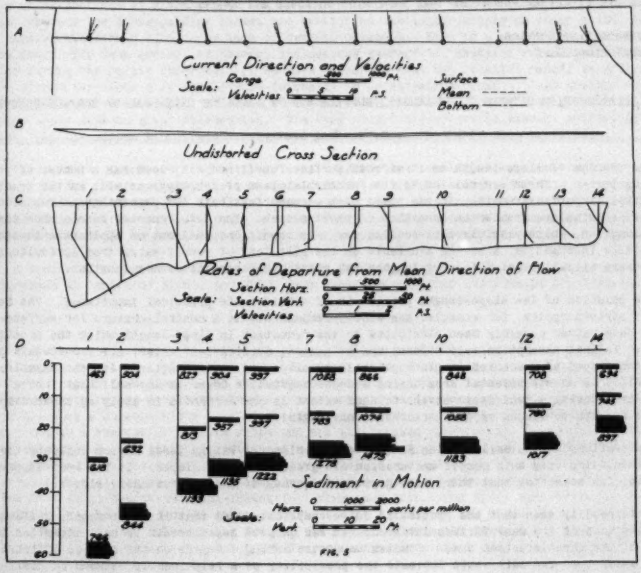

FIG. 5

Comparison of this graph with the true-scale cross-section of the River shown above suggests "circulation" as perhaps more truly descriptive and fortunate than "helical flow" as a general term for natural divergency in current-direction on stream-bends.

"D" shows the parts per million, sediment to water by weight, plotted for surface, for mid-depth, and for each foot of the lowermost 5 feet of the stream at each point of observation. Note that least sediment is carried in the general thalweg region--top, mid-depth, and bottom--despite the existence here of major velocities, major discharge, and a very actively caving bank. The greater concentration of sediment near the bed is in the region of convergent bottom-currents on the rim of the bar; at mid-depth and at the surface, it is in the region above bottom-current convergence where upward movements are indicated.

Apparently the caving banks here are not overloading bottom-waters with sediment. The cross-section circulation appears to bring relatively clear waters against the caving bank in such volume that very light loading in their sweep outward along the bottom is sufficient for removing all the bank-detritus produced by very vigorous caving. The bank here at the time of observation was caving at an average rate of about 4 feet a day to a depth of 100 feet below bank-level.

In summary, the systematic divergency of current-direction on stream-bends seems to be indicated, first of all, by the fact of superelevation of waters toward the outer bank of the bend. Such cross-channel slopes would appear, necessarily, to impose a constant deflective force from surface to bed throughout each water-column. Constant centrifugal resistance to this deflective force in cross channel-direction seems necessarily established by variation in paths of curvilinear motion distributed according to velocity-variations in the vertical column.

The experimental tests with coal and chat, with surface-floats and with deep-set floats, and with the photographic current-direction recorder all join in indicating the existence of systematic cross-section components of motion in thorough keeping with this theory of forces. And, lastly, the distribution of sediment, as determined by entirely different means, appears to lend support to both the theory and to the authenticity of the results of the more direct tests and measurements of current-behavior that were made on these stream-bends.

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SOME RELATIONSHIPS BETWEEN SLOPE-LENGTH, SURFACE-RUNOFF, AND THE SILT-LOAD OF SURFACE-RUNOFF

G. W. Musgrave

The problem of slope-length as it affects surface-runoff and silt-load has a number of interesting phases. These are related to the fundamental laws of hydrology as well as the practical control of surface-runoff. It has often been assumed that both the percentage of runoff and the total erosion are greater on long than on short slopes. The data reported herein show that this assumption, while possibly well-founded for some conditions, may not be applicable to others. Little information, also, is available on the silt-load of runoff-water from agricultural fields where slopes are of differing lengths but where other conditions are constant.

The solution of the slope-length problem is of considerable practical importance. The benefits of strip-cropping, for example, now widely recommended as a control-measure for surface-runoff, have rather commonly been attributed to the reduction in slope-length which the practice entails. Is this assumption well-founded and of general application? Also, are runoff-data secured from slopes of specified length applicable to slopes of other lengths? If, for example, the runoff from an experimental area having a dense vegetative cover is one-half that from a similar area having a less dense cover, to what extent is one warranted in applying these comparative results to slopes of greater or of less length?

Observations at the Soil Erosion Station of the Missouri Valley Loess Region indicate that for certain rains only both runoff and erosion are greater on long slopes. It has been apparent, also, for some time that there is a greater frequency of runoff from short slopes.

It is readily seen that the problem is quite complicated and that it is extremely difficult to isolate each of the many factors involved. It can only be hoped herein to call attention to several of the more important ones. Studies conducted during the year on the rate of infiltration of water into the soil would indicate the possibility of a relationship between rainfall-

intensity and the rate of infiltration of the soil-medium which offers a logical explanation for results otherwise difficult to interpret.

Literature

F. L. Duley and F. G. Ackerman (Runoff and erosion from plots of differing lengths, J. Agric. Res., v. 48, No. 6) have reported results from plots of 3-foot width and lengths of 10, 20, 40, and 100 feet. These plots were upon Derby silty clay-loam, which it is stated is fairly permeable and has no clay-pan, but does have apparently a rapid rate of absorption. Water was applied by sprinkling cans in 18 records, and in addition records are reported for three natural rains. The plots were without vegetative cover and were hoed and raked before the beginning of each series of tests. Tests were run on 4 and 4.4 per cent slopes. The results showed a larger percentage of runoff from short slopes than for long slopes, on the average, for all rates of application used.

The authors note one application, however, of 1 inch in 30 minutes which gave no runoff. It might, therefore, be inferred that the infiltration-rate of the soil was above this rate. The maximum intensity of application was 1 inch in 15 minutes, although several applications were applied immediately following heavy applications, one instance of which is noted as being 6 minutes after the first application. It is concluded: "There was a larger percentage of surface-runoff from the short plots than from the long ones. This seemed to be true with both the heavy and light applications of water for the plot-lengths under consideration. It is also noted that the results of the erosion-measurements of these plots were less consistent than the results for runoff."

H. H. Bennett (Dynamic action of rains in relation to erosion in the humid region, Trans. Amer. Geophys. Union, 15th annual meeting, pp. 474-488, 1934) gives the average annual soil- and water-losses from seven soils at seven of the Erosion Experiment stations for slope-lengths of 36.3, 72.6, and 145.2 feet. He states that these data are enough to show that this is a deeply complex problem and that our investigations have not gone far enough to throw a great deal of light on the mechanics involved. On some soils both erosion and runoff are greater on uniform slope cross-sections of short length, as in the instance of the Houston black clay of central Texas, whereas the corresponding losses are greater on the longer slopes on other soils, as in the case of the Vernon fine sandy loam of central Oklahoma. This is a matter not easy of explanation." The data quoted, of course, include the averages of whatever rain-intensities prevailed during the period recorded. If we were to assume that the relative runoff is greater on short slopes for certain ratios of rain-intensity to infiltration-capacity, and greater on the long slopes with other ratios, it would be probable that a combination of both groups in a single average would show no great differences. The very slight difference in average percentage of runoff from the slopes of different lengths cited by Bennett would be thus explained.

Furthermore, there are comparatively small differences in slope-length included in these series. If the relative runoff from slopes of different length bears a definite relationship to rainfall-intensities and soil infiltration-rates, it would be necessary in conclusive studies to have sufficient differences in length of slope such that the increase in time for infiltration on long slopes would be great enough to provide measurable differences in runoff.

A series of plots has been installed at the Clarinda Station in which there are greater differences in length of slope, and from these plots some further information has been obtained.

Methods

In 1932 three plots for a length-of-slope study were laid out at the Clarinda Station, selecting as the basis of length the longest practicable slope which was available after giving due consideration to uniformity of soil and suitable topography. A second slope one-half this length and a third one-fourth the length of the longest plot were installed adjacently. These plots all have a uniform width of 42 feet, the lengths being 630 feet, 315 feet, and 157.5 feet. They lie upon a reasonably uniform slope and are all treated identically, being cropped to corn continuously with rows in the direction of slope and plowed, planted, and cultivated on the same days. They all receive annually a winter cover-crop of rye and vetch. At the foot of each slope are installed a silt-trap and water-sampler of the square-notch divisor-type permitting the measurement of total water- and soil-losses following each rain. The plots have three Weather Bureau type rain-gages adjacent to them, one situated at the top of the slope, one approximately half way down, and the other at the foot of the slope. Within 100 feet of the experiment there is also installed a recording gage of the Fergusson type from which rain-intensity records are available.

These plots are located upon a soil which is quite permeable. Infiltration-rates have been determined for a large number of conditions (G. W. Musgrave, The infiltration of soils in relation to the control of surface-runoff and erosion, J. Amer. Soc. Agron., in press; also unpublished data). This soil under average moisture-content and without vegetative cover, and also without cultivation, has an infiltration-rate approximating 3/4 inch per hour. When the soil is cultivated and dry, the infiltration-rate is more than double, and when saturated, it is somewhat lower than the above amount. The amount of infiltration is, of course, greatly affected also by the vegetative cover at the time of record, the total amount being greater in the presence of a dense cover and lower in the absence of any cover.

Results

From August 15, 1932, to December 31, 1934, eighteen runoff-records have been obtained from this series of experiments. The combined totals for all rains causing runoff during this period are given in Table 1.

Table 1--Amount of runoff and silt-load from slopes of three different lengths, totals for all rains combined

Slope-length	Runoff[a]				Silt-load[c]
	1932[b]	1933	1934	Total	
feet	inches	inches	inches	inches	lbs/ft^3
630	0.84	2.54	0.64	4.02	5.29
315	0.76	2.69	1.06	4.51	3.18
157.5	1.25	3.33	1.19	5.77	1.56

[a]Calculated as soil-free water.

[b]Experiment established August 1, 1932.

[c]Includes total soil removed from slope, whether in suspension or not, calculated as pounds of dry soil per cubic foot runoff.

It is seen that the runoff was greatest from the short slope and least from the long slope when all rains are combined for the entire period. The silt-load, however, is greatest from the long slope and least from the short slope.

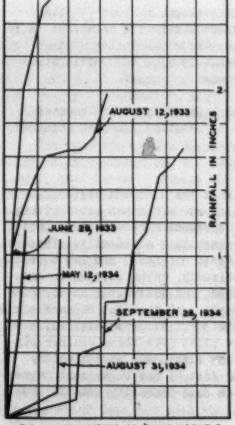

FIG. 1—INTENSITIES OF RAINS, GROUP I

Some of the rains included in Table 1 produced more runoff from the long slope and therefore it is of interest to examine the data more closely. For this purpose the records have been divided into two groups as accurately as possible, Group 1 containing records from rains of intensities appreciably above the infiltration-rate of the soil, and Group 2 containing those which approximate, or are but slightly above, the infiltration-rate. Five of the 18 records fall in the first and 13 in the second group.

This classification is necessarily somewhat arbitrary although based upon an extensive study of infiltration-rates for this soil under various conditions of structure and moisture-content. The high-intensity rains are shown graphically in Figure 1 and the low-intensity rains in Figure 2. The rains of May 12, 1934, and of August 17 and 18, 1932, are particularly difficult to classify. As the former has a maximum intensity above that of the low group, it has been included in the high-intensity class. It occurred, however, on freshly-prepared soil prior to planting of corn and behaves like a rain close to the infiltration-rate. Also, the rain of August 17 and 18, 1932, followed upon the large rain of August 15, 1932, and while of low intensity the runoff-record simulates the rains much above the infiltration-capacity. Should these two rains be regrouped each in the opposite classes, the conclusions which are drawn hereinafter would be further emphasized.

The volume of surface-runoff and the silt-load for the groups of rains which are appreciably above the infiltration-capacity of the soil for the three comparable lengths of slope are given in Table 2.

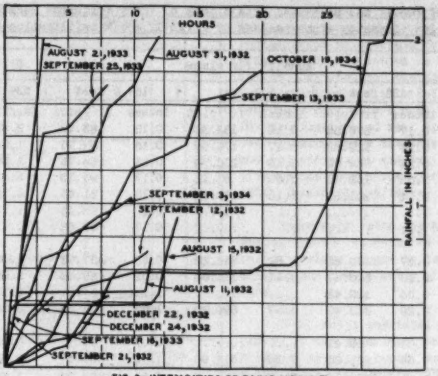

FIG. 2--INTENSITIES OF RAINS, GROUP II

Table 2--Amount of runoff and silt-load from slopes of three different lengths for Group 1, that is, rains of high intensity and appreciably above infiltration-capacity of soil

Date	Precipitation	Runoff[a] for slope						Silt-load[b] for slope		
		630 feet		315 feet		157.5 feet		630 ft	315 ft	157.5 ft
1933	inches	inches	ft³/plot	inches	ft³/plot	inches	ft³/plot	lbs/ft³	lbs/ft³	lbs/ft³
June 27	2.88	0.31	680.64	0.13	134.81	0.12	66.20	20.14	15.88	14.71
June 29	1.13	1.13	2495.26	1.07	1119.03	0.59	323.12	9.98	7.74	4.76
1934										
May 12	1.30	0.13	292.24	0.21	222.37	0.18	101.00	2.09	1.34	1.12
Aug. 31	1.21	0.03	66.63	....	.....	....	.....	9.30	....	....
Sep. 28	1.71	0.07	148.50	0.07	68.79	....	.....	0.50	0.01	....
Total	8.23	1.67	3683.27	1.48	1545.00	0.89	490.32	10.84	7.18	5.35

[a]Calculated as soil-free water. [b]Includes total soil removed from slope, whether in suspension or not, calculated as pounds of dry soil per cubic foot runoff.

The total of the intensive rains was 8.23 inches. Of this 1.67 surface-inches from the 630-foot slope, 1.48 inches from the 315-foot slope, and 0.89 inch from the 157.5-foot slope were lost as runoff. The total soil removed and retained in the silt-box, together with the material in suspension when calculated upon the dry-weight basis, is shown in the last three columns of Table 2. For these rains each cubic foot of runoff-water removed from the long slope an average of 10.84 pounds of soil, from the intermediate slope 7.18 pounds, and from the short slope 5.35 pounds. Some minor inconsistencies in trend are found in the volume of runoff, but the direction of trend for the silt-load is the same for each record.

Quite different results are found for the low-intensity rains as shown in Table 3. The larger number of rains in this low-intensity group totalled 17.42 inches. Of this amount 2.34 inches from the long slope, 3.02 inches from the intermediate slope, and 4.88 inches from the short slope were lost as runoff. The direction of trend here is opposite to that of the group of high-intensity rains.

The average silt-load was 1.34, 1.22, and 0.87 pounds per cubic foot of runoff for the long, intermediate, and short slopes, respectively. The trend is similar to that in the first group, but the general level is much lower.

Table 3--Amount of runoff and silt-load from slopes of three different lengths for Group 2, that is, rains of low intensity approximating or slightly above infiltration-capacity of soil

Date	Precipitation	Runoff[a] for slope						Silt-load[b] for slope		
		630 feet		315 feet		157.5 feet		630 ft	315 ft	157.5 ft
1932	inches	inches	ft^3/plot	inches	ft^3/plot	inches	ft^3/plot	lbs/ft^3	lbs/ft^3	lbs/ft^3
Aug. 15	0.93	0.17	376.59	0.13	133.37	0.15	83.32	2.43	4.21	4.61
Aug.17,18	0.87	0.24	529.63	0.17	179.67	0.16	87.76	1.24	3.05	3.24
Aug. 31	2.29	0.24	537.74	0.19	200.74	0.28	154.75	1.84	3.55	2.80
Sep. 12	0.47	0.05	103.42	0.09	93.11	0.17	91.33	5.64	3.81	2.02
Sep. 21	0.71	0.14	301.50	0.18	182.93	0.15	81.60	0.76	0.86	1.24
Dec. 22	0.43	....	.....	....	.....	0.17	93.20	....	....	....
Dec. 24	0.44	....	.....	....	.....	0.17	94.52	....	....	0.002
1933										
Aug. 21	3.70	0.67	1470.80	0.80	838.22	0.83	457.73	1.86	1.30	1.28
Sep. 13	1.86	0.10	210.23	0.11	110.84	0.09	50.88	1.58	1.79	2.25
Sep. 16	0.35	0.06	122.42	....	.....	....	.....	0.11	....	....
Sep. 25	1.92	0.28	615.45	0.57	599.29	1.70	935.57	0.38	0.19	0.20
1934										
Sep. 3	1.03	0.03	69.41	....	.....	....	.....	0.52	....	....
Oct. 19	2.62	0.38	831.38	0.78	813.96	1.01	556.57	0.23	0.15	0.10
Total	17.42	2.34	5168.57	3.02	3152.13	4.88	2687.23	1.34	1.22	0.87

[a]Calculated as soil-free water. [b]Includes total soil removed from slope, whether in suspension or not, calculated as pounds of dry soil per cubic foot runoff.

The percentage of runoff from both groups was as follows:

Slope	High-intensity rains	Low-intensity rains
630 feet	20.3 per cent	13.5 per cent
315 feet	18.0 per cent	16.5 per cent
157.5 feet	10.8 per cent	28.0 per cent
Weighted average	17.5 per cent	16.4 per cent

The average percentages of runoffs from the two groups of rains are not very different, but the very distinct relative difference in runoff from the different lengths of slopes for the high and low intensities is clearly apparent.

The total amount of soil moved per unit of area is a product of volume of runoff and silt-load, These amounts are as follows:

Slope	High-intensity rains	Low-intensity rains
630 feet	32.86 tons per acre	5.70 tons per acre
315 feet	18.26 tons per acre	6.35 tons per acre
157.5 feet	8.64 tons per acre	7.68 tons per acre

Thus, with both the highest volume of runoff and the highest silt-load coming from the long plot with high-intensity rains, the total amount of soil moved (32.86 tons per acre) is naturally greater. On the other hand, for the low-intensity rains the long plot yields less volume of runoff but a heavier silt-load than the short plot. It is not surprising, therefore, to find that the amount of soil moved from a unit-area does not vary greatly with slope-length for these lighter rains.

There is but one plausible explanation for the greater silt-load coming from the long plot for both groups of rain, namely, that the velocity of runoff most probably is greater on the long slope. There may be other contributing factors, such as somewhat greater concentration of the runoff into rivulets and less movement in uniform thin sheets, which obviously is common to the long slopes. However, it is believed the greater effect upon silt-load may accrue from the movement of runoff over successively deeper films of water as it proceeds from the top toward the bottom of the slope, and probably thus moving with ever-increasing velocity.

Thus, for the high-intensity rains both the percentage of runoff and the silt-load in pounds per cubic foot are greater on the long slope. For the low-intensity rains, however, the percentage of runoff is much less on the long slope, while the silt-load is slightly higher on the long slope.

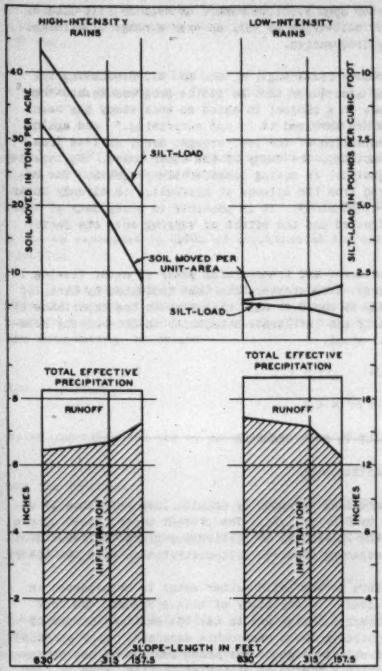

FIG. 3—RELATION OF INFILTRATION RUNOFF AND SILT-LOAD TO SLOPE-LENGTH

A slightly different view of these relations is shown in Figure 3. The calculated infiltration in relation to runoff and total effective precipitation is seen to be greater on the long plot for the low-intensity rains. The conditions are in brief: (a) A highly permeable soil with a high infiltration-rate; (b) applications of rain approximating or but slightly above the infiltration-rate; and (c) consequent greater total infiltration on the long slope where more time for water-intake is available.

Conversely, with the high-intensity rains giving greater velocity to the runoff from the long slope, there is less time for infiltration and consequently greater runoff occurs.

Thus, while the total runoff for the period of the experiment shows that the greatest relative runoff occurred on the short slope, it appears that this is due to the fact that most of the rains fell at low intensities and at rates close to the infiltration-rate of the soil. For any period in which high-intensity rains predominate, entirely opposite results may be found.

Quite possibly these trends in relative runoff may be more striking on the highly permeable soil upon which this experiment is located than upon many other soils of the United States. At least, such an assumption is logical and has some corroboration in the data of certain other studies which are now under way on soils of differing infiltration-rates.

One may speculate upon effects similar to the above in the data cited by Bennett. Although the slopes are shorter and smaller differences are to be expected, there is found at least nothing contradictory. Probably the most impermeable soil included among the seven cited is the Kirvin Series. One might anticipate greater runoff from the long slope on this soil and the trend does appear to be in such direction. Among the permeable soils are the Colby, Marshall, Clinton, and, when dry, the Houston. On these one might anticipate relatively less runoff on the longer slopes, and if a trend may be said to exist it is in this direction.

In the results of Duley and Ackerman the fact that in one instance at least an application of 1 inch in 30 minutes gave no runoff indicates that a highly permeable medium--at least under the conditions of tillage as practiced--was used. Thus, it appears that the applications in general were not greatly above the infiltration-capacity and the results show less runoff from the longer slopes. The silt-load in general was much greater on the long slopes.

The thesis here set forth, namely, that the relative runoff from slopes of different lengths is dependent largely upon ratios of rainfall-intensity to soil-infiltration, has some rather broad implications. For example, such a premise, if thoroughly established and shown to be of general application, would logically lead to the following conclusions: (a) Of two soils, one more permeable than the other and both subjected to the same variations in amount and intensity of rainfall, other things being equal, the impermeable soil will show relatively greater losses from long slopes; (b) such practices as terracing may be expected to show greater relative benefits on impermeable soils than upon permeable soils; (c) wide spacing of terraces (giving in effect long slopes) should prove to be relatively better on permeable than on impermeable soils and also, in the practice of strip-cropping, wider strips may be used on permeable than on impermeable soils; and (d) soil treatments which improve the infiltration-capacity of the soil may be expected to show greater relative effects on long slopes than on short slopes.

The importance of the length-of-slope factor upon relative runoff as well as silt-load of runoff warrants extensive study over a range of soil-types as well as over a range of rainfall-conditions differing particularly in intensity-frequencies.

E. W. Lane (The silt-problem, Proc. Amer. Soc. Civil Eng., v. 61, No. 3), discussing the silt-problem of large streams, states: "It may seem queer that so little progress toward the development of a definite science should be made in a subject to which so much study has been given, but when reflecting on how many factors are involved it is not surprising." And again: "Although the prospect of a quantitative determination of the load brought down, derived from the various factors involved, does not seem practical, the study of the other phase, the capacity of a stream to transport material of a given quality, is making considerable progress. The relations between a number of the factors involved from the science of hydraulics is already known and the remaining ones are being subjected to close study. It is possible to study many of these relations ... where the conditions can be controlled and the effect of varying only one factor at a time observed."

The limitations in our knowledge of the movement and transporting power of water flowing in thin sheets from agricultural areas is, of course, even greater than that indicated by Lane for large streams. In the present paper it can only be hoped to call attention to the importance of the relations existing between rainfall-intensity and infiltration-capacity in determining relative soil- and water-movement from agricultural areas.

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DISTRIBUTION OF SILT IN OPEN CHANNELS

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A theory of silt-distribution in open channels as advanced by Schmidt [see reference 17 under section "References] was recently outlined by O'Brien [13]. The present paper, based upon a thesis on file at the Hydraulic Laboratory of the University of California, gives the results of a study of available data for the purpose of comparing observed silt-distribution with the theory.

As used in this paper, the term "silt" refers to the solid matter which is transported in suspension, but not to that which moves as bed-load. In any study of silt-problems, the cost and difficulty of securing and analyzing silt-samples oblige one to use the smallest number of samples that will represent the mean silt-concentration with reasonable accuracy. Many studies have been made to determine the distribution of silt throughout the cross-section of the stream-channel. Unfortunately, in the absence of a rational theory of silt-distribution, many factors influencing the distribution were not recognized as such, and no attempt was made to determine them.

As given by O'Brien, the equations connecting the distribution of silt with the turbulence of the stream are

$$\tau = \epsilon(dv/dy) \tag{1}$$

$$\omega m + (\epsilon/\rho_f)(dm/dy) = 0 \tag{2}$$

Here τ is the apparent shearing force per unit-area, ϵ is the austausch-coefficient or mechanical viscosity, v is the velocity of the water in the direction of flow, y is the vertical dimension, ω is the settling velocity of the silt in still water, m is the concentration of silt, and ρ_f is the density of the water. (These symbols differ somewhat from those used by O'Brien.)

The austausch-coefficient as a function of the hydraulic elements of the stream--As equation (1) shows, the shearing force cannot be transmitted through the point of maximum velocity. Selecting this point as the origin of y, we can write, where w is the unit-weight of water and s is the energy-gradient,

$$\epsilon = (-wys)/(dv/dy) \tag{3}$$

This approximates the more general equation used by Leighly [10]. In order that the point of maximum velocity may be below the surface, a shearing force must be exerted at or near the surface. That the atmospheric resistance is not the only cause of this phenomenon has long been recognized, and various explanations have been offered. The double-spiral-motion theory advanced

originally by Stearns [18] and later by Gibson [6] appears to be the most logical, and attempts to show how the shearing force can be transmitted from the region above the maximum velocity to the bed.

The austausch-coefficient is a function of the vertical velocity-curve and the hydraulic elements of the stream. Equation (3) may be written

$$\epsilon = (-wR^2s/V)[Vy/R^2(dv/dy)] \tag{4}$$

where $[Vy/R^2(dv/dy)]$ is a dimensionless function of the velocity-distribution. Combining this equation with Manning's formula

$$V = 1.49R^{2/3}s^{1/2}/n \tag{5}$$

ϵ can be expressed in terms of any three of the variables V, R, n, and s, and the dimensionless function.

If the vertical velocity-curve is a parabola with its major axis horizontal and coinciding with the thread of maximum velocity, a shape it approximates except near the bed, the austausch-coefficient is constant, and the equation can be integrated directly. Rearranging equation (3) and integrating, we obtain

$$v = [V_m - (wy^2s/2\epsilon)] \tag{6}$$

and

$$\epsilon = wy^2s/2(V_m - v) \tag{7}$$

An an approximation let us assume that $(V_m - v) = 0.5\ V$ when $y = R$. Then

$$\epsilon = wR^2s/V \tag{8}$$

and the function

$$Vy/R^2(dv/dy) = -1 \tag{9}$$

If s is eliminated from equation (4) by substitution from Chezy's formula instead of Manning's, we obtain

$$\epsilon = (-wRV/C^2)[Vy/R^2(dv/dy)] \tag{10}$$

Assuming that R is a function of D and that the velocity-curve is parabolic, and combining constants

$$\epsilon = KVD = Kq \tag{11}$$

which is the equation assumed by Jeffreys [9] for the region between the surface and the boundary-layer.

The function $Vy/R^2(dv/dy)$ was computed for the vertical velocity-curve used by the Mississippi River Commission [12]. It was found to vary from a minimum of about -0.5 at the surface and near the bed to a maximum of about -2 at mid-depth. According to Leighly [11], the regions of maximum turbulence in a stream-channel are toward the sides of the region of maximum velocity and nearer the bed.

Distribution of silt in a vertical section--Rearranging equation (2) and writing

$$dm/m = -\omega\rho_f dy/\epsilon \tag{12}$$

and integrating the left-hand side

$$\log m - \log m_0 = -\omega\rho_f \int_0^y (dy/\epsilon) \tag{13}$$

from which

$$m = m_0\, e[-\omega\rho_f \int_0^y (dy/\epsilon)] \tag{14}$$

Here m_0 is the silt-concentration at $y = 0$, the position of which is arbitrary. This equation cannot be completely integrated unless ϵ is constant or can be expressed as a function of y.

The value of $\int_0^y dy/\epsilon$ is equal to the area under the curve $1/\epsilon$ plotted as a function of y and can

be determined graphically from values of ϵ computed from the velocity-distribution.

If ϵ is constant, equation (14) becomes

$$m = m_0 \, e(-\omega\rho_f y/\epsilon) \tag{15}$$

which is essentially the equation determined experimentally by Hurst [8] and Richardson [15].

Settling velocity of silt--The resistance to motion of solids in viscous fluids has been extensively studied. The method commonly used in presenting the results of these studies is to express the coefficient of resistance, C_r, as a function of Reynold's number, R_e. Reynold's number is a characteristic length, usually taken as the diameter of the solid, multiplied by the velocity and divided by the kinematic viscosity of the fluid. For a sphere $R_e = 2r\omega\rho_f/\mu$. The coefficient of resistance is defined by equating the force producing motion to the force resisting motion, expressed as the coefficient of resistance times the dynamic pressure acting on the cross-sectional area of the solid. For a sphere,

$$(4/3 \; g\pi r^3(\rho_p - \rho_f) = C_r \pi r^2 \rho_f \omega^2/2 \tag{16}$$

from which

$$\omega = \sqrt{8 \; gr(\rho_p - \rho_f)/3 \; C_r \rho_f} \tag{17}$$

For spheres, Stoke's law [19] has been verified experimentally for $R_e < 0.2$ by the researches of Allen [1], Arnold [2], Wieselsberger [22], and others. It can be expressed by the equation

$$\omega = 2 \; gr^2(\rho_p - \rho_f)/9\mu \tag{18}$$

or

$$C_r = 24/R_e \tag{19}$$

For higher values of R_e, the coefficient of resistance departs from this relation and reaches a minimum value of about 0.38 at $R_e = 4000$. (There is another higher critical point at which the coefficient of resistance reaches a lower value, but it is entirely out of the range in which we are interested.)

Wadell [20], who has reviewed the subject of settling velocity of solids in fluids, shows that the coefficient of resistance of solids other than spheres is higher than for spheres and is a function of the shape of the solid as expressed by the symbol ψ, the ratio of the surface-area of a sphere to that of a solid of equal volume but different shape. Hazen [7] gives a table of settling velocities of sand grains. Rubey [16] recently proposed a formula for settling velocities that can be represented by the equation

$$C_r = (24/R_e) + 2 \tag{19}$$

He showed that this was in substantial agreement with Richards' [14] data on quartz and galena fragments up to a Reynold's number of about 1000.

Figure 1 shows the relation of settling velocity, nominal diameter, coefficient of resistance, and Reynold's number for spheres and solids of other shapes. The close agreement of Wadell's formula with the experimental curve up to $R_e = 3000$ is apparent. Figure 2 shows the relation of diameter of particle to settling velocity in English units, as determined experimentally for spheres and also as given for sand by Hazen and by Rubey's formula. With the exception of Hazen's curve, these graphs are based upon a silt-density of 5.14 (2.65 c.g.s. units) and upon the viscosity of water at 20° C.

The settling velocity of silt in water also depends upon the chemical composition of the water, since it affects the dispersion and flocculation of the silt-particles. Breazeale [3] concludes that the silt in the Colorado River is in a highly dispersed state and that the quality of the water, except at low stages, is such that dispersion is maintained.

Comparison of theoretical and observed silt-distribution--The most complete data that the writer has been able to obtain from which an accurate comparison of the theoretical and observed silt-distribution can be made are those of Fortier and Blaney [5] for the Colorado River and Imperial canals. These data include simultaneous measurements of velocity and silt-concentration at several positions in the vertical section, together with sieve-analyses of the silt. As the slope of the energy-gradient is usually not given, estimates are necessary in order to calculate

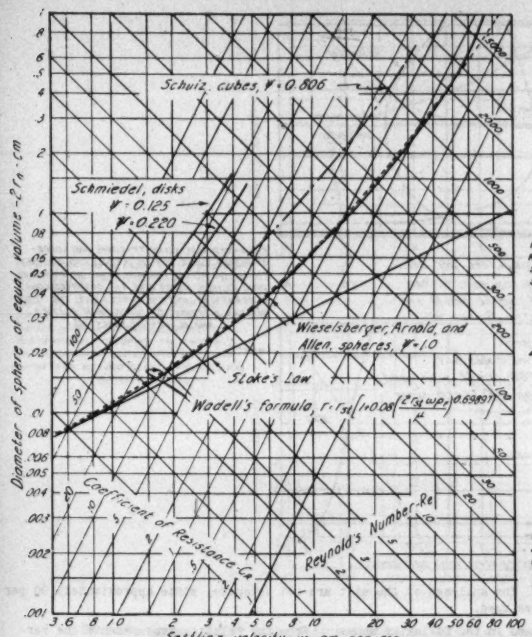
Diameter of sphere of equal volume - r = cm
Settling velocity - w - cm per sec.
Schulz, cubes, Ψ = 0.806
Schmiedel, disks
Ψ = 0.125
Ψ = 0.220
Wiesselsberger, Arnold and Allen, spheres, Ψ = 1.0
Stokes Law
Wadell's formula
Coefficient of Resistance Cr
Reynold's Number Re

FIG. 1—RELATION OF SETTLING VELOCITY, NOMINAL DIAMETER, COEFFICIENT OF RESISTANCE, AND REYNOLD'S NUMBER FOR SOLIDS OF DENSITY 2.65 IN WATER AT 20°C (DATA FROM WADELL [20,21])

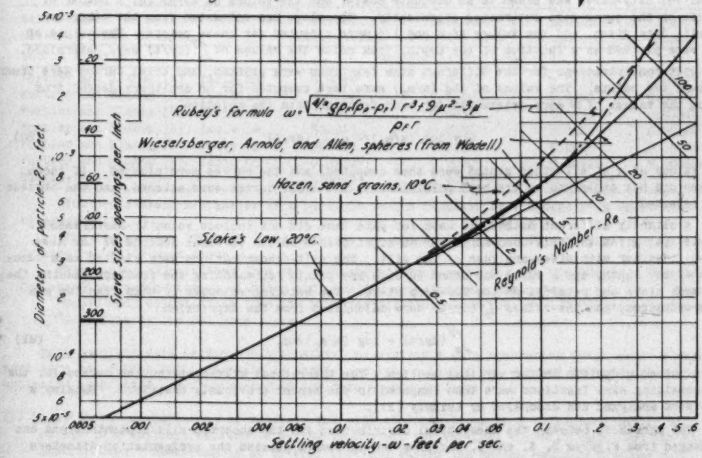
Diameter of particle - D - feet
Settling velocity - w - feet per sec.
Rubey's formula
Wiesselsberger, Arnold, and Allen, spheres (from Wadell)
Hazen, sand grains, 10°C
Stokes Law, 20°C.
Reynold's Number - Re

FIG. 2—RELATION OF SETTLING VELOCITY AND NOMINAL DIAMETER OF SILT IN WATER IN ENGLISH UNITS; ASSUMED DENSITY OF SILT 5.14=2.65 C.G.S. UNITS (FROM DATA BY WADELL [20], RUBEY [16], AND HAZEN [7])

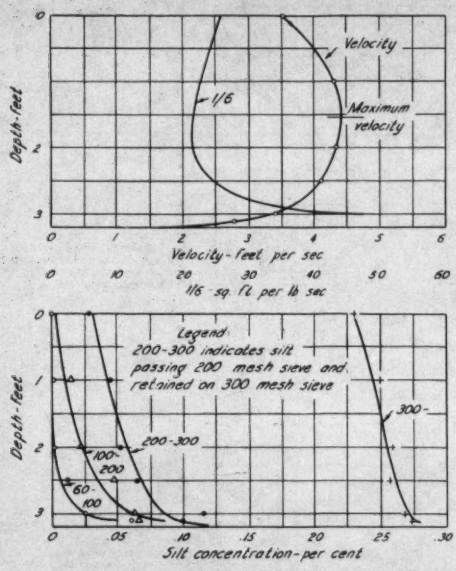

FIG. 3—VERTICAL VELOCITY-CURVE AND CORRESPONDING CURVE FOR 1/ε (ABOVE) AND SILT-DISTRIBUTION (BELOW) FOR ASH CANAL AT BOUNDARY, JUNE 23, 1920; POINTS GIVE THE OBSERVED CONCENTRATIONS AND THE CURVES GIVE THE THEORETICAL DISTRIBUTION (DATA FROM FORTIER AND BLANEY [3], TABLE 26)

the austausch-coefficient. The analyses of the silt are not adequate, since approximately 90 per cent passed the finest sieve used.

These data were analyzed in the following manner: From the velocity-measurements the vertical velocity-curve was drawn to an adequate scale, and the values of dv/dy for a number of points on the curve were determined graphically. The slope was estimated from the other hydraulic data given, and the values of ϵ and $1/\epsilon$ were computed for these points. The values of $1/\epsilon$ were plotted as a function of the depth, from which the values of $\int_0^y (dy/\epsilon)$ were determined. The silt-concentrations for the different size fractions were plotted, and trial curves were drawn through the points. The values of $\log (m/m_0)$ were then computed for an arbitrary depth, from which the values of ω were determined for each fraction from the relation

$$\omega = \log (m/m_0)/-\rho_f \int_0^y (dy/\epsilon) \qquad (20)$$

The values of m at all other depths were then computed, and the curves were plotted. If these curves did not appear to be the best possible fit, the trial curves were altered, and the process was repeated.

A slightly different method was used for data that did not include velocity-measurements. Buckley [4] gives the silt-concentrations at eight points in the vertical section of the Nile River, together with sieve-analyses of the silt. The silt-concentrations were plotted as a function of the depth, and a curve was drawn through the points representing the fraction passing the 100-mesh sieve and retained on the 200-mesh sieve. The settling velocity of this fraction was then estimated, and the values $\int_0^y (dy/\epsilon)$ were calculated from the expression

$$\int_0^y (dy/\epsilon) = \log (m/m_0)/\omega\rho_f \qquad (21)$$

for a number of points in the vertical section. The theoretical silt-distribution curves for the two remaining size fractions were then computed in the manner previously described. Buckley's data were analyzed and discussed by Leighly [11].

The agreement between the theoretical distribution and the observed silt-concentrations can be judged from Figures 3, 4, and 5, and from the agreement between the sedimentation-diameters determined from the calculated settling velocities as given in Table 1.

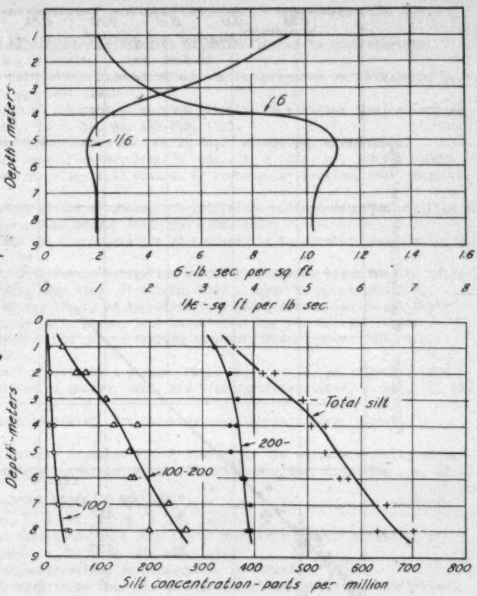

FIG. 4—VARIATION IN c AND 1/c CORRESPONDING TO SILT-DISTRIBUTION CURVES FOR NILE RIVER FOR MATERIAL PASSING 100-MESH SIEVE AND RETAINED ON 200-MESH SIEVE (ABOVE) AND SILT-DISTRIBUTION (BELOW); POINTS REPRESENT THE OBSERVED CONCENTRATIONS AND CURVES THE THEORETICAL DISTRIBUTION BASED UPON ARBITRARY CURVE FOR 100-200 FRACTION (DATA FROM BUCKLEY [4])

Table 1--Comparison of calculated sedimentation-diameters and sieve-openings[a]

Sieve-sizes[b]	60-100	100-200	200-300	>300
Sieve-openings in inch	0.0087-0.0055	0.0055-0.0029	0.0029-0.0018	<0.0018
Source of data	Sedimentation-diameter in inch			
Fortier and Blaney [5], Table 26	0.0049	0.0030	0.0018	0.00071
Fortier and Blaney [5], Table 27	0.0049	0.0026	0.0020	0.00067
Fortier and Blaney [5], Table 28	0.0047	0.0032	0.0020	0.00047
Fortier and Blaney [5], Table 54	0.0047	0.0035	0.0028	0.00126
Fortier and Blaney [5], Table 55	0.0049	0.0027	0.0020	0.00075
Fortier and Blaney [5], Table 56	0.0067[c]	0.0032[c]	0.0022[c]	0.00083[c]
Buckley [4]	0.0047[d]	0.0035[d]	0.0009[de]	

[a]The sedimentation-diameter of a particle is the diameter of a sphere with equal settling velocity.

[b]The designation "60-100" indicates that the material passed a 60-mesh sieve and was retained on a 100-mesh sieve.

[c]Based upon calculations from the silt-distribution curve for the 200-300 size-fraction for which the sedimentation-diameter and settling velocity were estimated.

[d]Based upon calculations from the silt-distribution curve for the 100-200 size-fraction.

[e]Silt passing the 200-mesh sieve.

More complete data needed--Unfortunately the available data upon which these studies were made were not sufficiently complete to permit accurate calculations without introducing certain estimated quantities. For such studies the data should include:

(1) Simultaneous measurements of velocity and silt-concentrations at a sufficient number of points in a vertical section to define accurately the vertical velocity-curve and the silt-distribution. Measurements at several sections across the stream would be desirable.

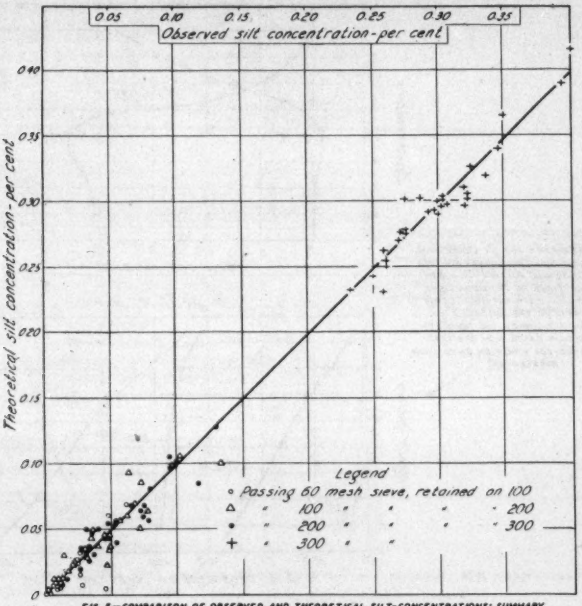

FIG. 5—COMPARISON OF OBSERVED AND THEORETICAL SILT-CONCENTRATIONS; SUMMARY OF ANALYSES OF DATA FROM FORTIER AND BLANEY [5]

(2) Mechanical analyses of the silt-samples, and determinations of the mean settling velocity of each size fraction. These determinations should be made in the water from the stream to avoid changing the state of flocculation or dispersion.
(3) An accurate determination of the energy-gradient of the stream.

For this purpose laboratory-studies may prove more valuable than studies on natural streams or canals because of the better control possible. Some of the difficulties inherent in field-work of this kind could be overcome in the laboratory.

The average silt-concentration at particular positions in the stream-channel over an appreciable time period is desired rather than the concentration of silt in a small volume of water that happens to be caught in the sampling device. For this purpose an improved method of securing silt-samples is needed. The use of a small centrifugal or gear-pump, so arranged that the entrance velocity to the sampling tube opening upstream could be adjusted to approximate the velocity of water at the position being sampled, is suggested. In this manner a sufficiently large sample could be obtained so that an accurate mechanical analysis of the silt could be made. Although a sampling device of this kind may be difficult to use on a large stream with an appreciable velocity, no difficulty should be experienced in using it in the laboratory.

Conclusions--Although the theory of silt-distribution as outlined by O'Brien agrees very well with the data analyzed in this paper, the practical applications of the theory are sufficiently important to justify additional studies.

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MODELS OF ESTUARIES

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An estuary is the meeting place of hydrology and oceanography and, from the nature of the problems met in studying the hydraulic phenomena associated with estuaries, it is difficult to decide in which field such studies properly belong. However, in defining the scope of the work of the Section of Hydrology, it appears that estuaries are included and an account of progress made in studying the estuary of the Columbia River may be of interest to hydrologists.

Estuaries are distinguished from harbors and bays by the fact that river-flow and the accompanying transport of sediment as well as tidal action have an important influence on the configuration of the bed and banks. They usually have the form of gradual enlargements of the river-channel into a tidal basin partially filled with river-deposits. The runoff may not be important in itself, but the capacity of the river for storing water during each tidal cycle is not negligible. This definition may not be satisfactory from the geological standpoint, but it does describe the type of model under consideration.

The problem of maintaining navigable depths at a river-entrance is one on which much work has been done without generally reliable quantitative rules of procedure being evolved. Each entrance has been improved by a process of "trial and error." Jetties, dikes, and other structures are built or channels dredged on the basis of past experience and many of these improvements have been notably successful, but the chance of failure is relatively great so that advance information on the probable effect of proposed work is desirable.

Small-scale hydraulic models are admirably suited to the solution of estuary-problems because proposed modifications may be investigated quickly and inexpensively under a range of conditions which might not occur in nature in a whole lifetime. However, the currents resulting from the combined effect of winds, tides, waves, river-flow, and salinity-gradients are complex and reproduction of them in a model is difficult. Before placing any reliance on the results of model-experiments made under such difficult circumstances, the degree to which the model corresponds with nature must be established. Previous experience with tidal models with movable beds is not extensive but the results are reported to be satisfactory.

As in several other branches of fluid mechanics, Osborne Reynolds led the way in the use of hydraulic models. His investigation of the estuary of the Mersey marked the beginning of the use of this valuable method but the great bulk of the models which have been built since his time have been concerned with rivers, canals, and structures, in which the flow is steady, rather than with tidal problems. The dimensions and other characteristics of the more important estuary-models built to date appear in Table 1.

Table 1

Prototype	Mersey	Mersey	Seine	Rangoon	Severn	Columbia[a]
Experimenter	Reynolds, 1885	Vernon-Harcourt, 1886	Vernon-Harcourt, 1886	Alexander Gibbs and partners, 1932	A. H. Gibson, 1932	U. S. Engineers, 1934
Purpose	Effect of regulating works	Effect of regulating works	Channel-improvement	Channel through outer bar	Effect of barrage on silting and currents	Estuary- and bar-channels
Range of tide (ft)	.....	.....	24	16-21	21-41	8
Diameter of sand in prototype (in)	0.008	.....	.....	.....	0.009	0.008
Diameter of sand in model (in)	0.006	0.0065	.....	Same as Rangoon River	0.007	0.0076
Horizontal scale	31800 10600	30000	40000	8068 7050	8500	3600
Vertical scale	960 396	500	400	192	200	64
Period of tide in model (sec)	40 80	.....	25	76	74	99
Reproduction of tides	Hinged trough	Hinged trough	Hinged trough	Plunger	Plunger	Pumping and gravity
Waves	Used in part	.....	No	By fans	No	Yes

[a] Scales and sizes of model refer to first series of experiments.

Model laws

The dimensions of most estuaries are such that if reasonable depths are to exist, the model must be distorted by using different horizontal and vertical scales. The use of distorted models is not justified whenever the conditions of flow are such that vertical accelerations are appreciable and this is equivalent to the statement that the curvature of the surface must be negligible (M. P. O'Brien, Analyzing hydraulic models for effect of distortion, Eng. News-Record, September 15, 1932). However, in an estuary, the vertical velocities and accelerations are so small and the curvature of the surface so slight that distortion of a model by choosing different horizontal and vertical scale-ratios is permissible. In fact, it appears that the use of different scales adversely affects the flow-conditions less in estuary-models than in any other type. The most important restriction on the distortion of the linear dimensions is not hydraulic but rather one of soil-mechanics, in that by an excessive distortion it might tacitly be assumed that sand-banks will stand at an angle greater than their angle of repose.

There has been some discussion of the reliability of, and technical justification for, distorted models and many of the arguments appear to be based on the conception of a model as a pictorial or topographic representation. To the writer a model is merely a mechanical means of solving the differential equations of fluid-motion for boundary-conditions which are too complex for mathematical representation, and any hydraulic system which can be used to predict the behavior of a prototype should be classed as a model whether or not there is any similarity of outline. Any kind of distortion is satisfactory provided that a reliable method of transferring data to the full-scale system can be discovered, and the use of true or simply distorted models is a convenience rather than a necessity. A simple method of transferring data has been worked out for models which "look" like the prototype and there is no reason for not using a simple geometrical relationship, such as a single scale for vertical dimensions and the same or another single scale for horizontal dimensions. As an example of the absence of geometrical similarity may be cited experiments in small rectangular channels intended to discover the law governing the transportation of bed-load. If a generally applicable relationship is obtained, the flow in these channels is truly a model of all rivers and streams as regards one feature, namely, bed-load movement. The same statement may be made regarding all experiments yielding generalizations.

No universal criterion for the necessary size of a model can be established because the size is directly dependent on the problem to be solved. Models are never strictly similar to their prototypes and whether to describe them as similar or not is entirely a question of the thoroughness of examination. A photograph of a model may be geometrically similar to a chart of the prototype but this correspondence cannot extend to such features as the viscous and capillary forces and generally is not true of the size and shape of sand-grains. The only valid generalization is that the boundary-conditions, including the inflow and outflow, must be reproduced in a manner sufficiently similar to that in the prototype and the size must be sufficiently great, that the particular phenomenon under investigation will be reproduced to a known scale. For example, a relatively small model of an estuary could be used to study improvements in the main channels but a much larger model would be necessary for an investigation of sedimentation in the shallow and quiet portions of the same estuary. The necessary size of a model depends not only upon the size and hydraulic characteristics of the prototype but equally as much upon the particular features of the prototype which are to be examined.

Starting from the equation for the velocity of advance of a shallow-water wave, $C = \sqrt{gD}$, Reynolds (Scientific Papers, v. 2, p. 393) obtained the model relationships for what he termed hydro-kinetic similarity. The principal assumption involved is that the water-velocities are proportional to the wave velocities. The scale-ratios are as follows, where the letter "b" indicates a ratio and the subscript indicates the quantity involved and all scale-ratios represent a magnitude in the prototype divided by the corresponding magnitude in the model:

Vertical dimensions	b_z	Volume of deposit or scour	$b_x^2 b_z$
Horizontal dimensions	b_x	Cross-sectional areas	$b_x b_z$
Water- and wave-velocities	$b_v = \sqrt{b_z}$	Horizontal areas	b_x^2
Time-intervals	$b_t = b_x/\sqrt{b_z}$	Hydrostatic and dynamic pressures	b_z
Rates of discharge	$b_q = b_x b_z^{3/2}$		
Tidal prism	$b_x^2 b_z$	Forces on horizontal areas	$b_x^2 b_z$
		Forces on vertical areas	$b_x b_z^2$
		Hydraulic radius (depends on shape)	b_z (approx.)

Having fixed the ratios of horizontal and vertical dimensions, the remaining scale-ratios would apply to a frictionless flow, but the amount of deviation which occurs in the flow of a liquid of small viscosity such as water depends largely upon the amount of distortion. The dimensions and velocities in the model must be such that the flow is turbulent and that capillarity does not have an appreciable influence. However, even if the flow is completely turbulent, as it is almost certain to be if the velocities are sufficient to move the bed-material, there is a source of error which should not be overlooked. For complete similarity, the slope of the water-surface should follow the ratio b_z/b_x, but from Manning's equation

$$b_s = b_n^2 b_v^2 / b_R^{4/3} \qquad (1)$$

Assuming that $b_v^2 = b_z$, $b_R = b_z$, and that Strickler's equation (Beiträge zur Frage des Geschwindigkeitsformel und der Rauhigkeitszahl für Ströme, Kanäle, und geschlossene Leitungen, Mitt. des Amtes für Wasserwirtschaft, Berne, 1923) for the relationship between Manning's n and the size of the bed-material is valid,

$$b_n = b_d^{1/6} \qquad (2)$$

$$b_s = b_d^{1/3} / b_z^{1/3} \qquad (3)$$

Here, d is the diameter of the bed-material. If the same or nearly the same material is used in the model as in the prototype, $b_d = 1$ approximately. In the Columbia River model, $b_z = 64$ and the friction-slopes in the model are only four times those in nature, whereas this ratio should be 3600/64.

The effect of this reduction in friction-effect is twofold. The velocities and inertial effects in the model are probably greater than they should be and, because of the decreased friction, the range of tide does not decrease as rapidly as it should during progress of the tidal wave through the estuary and into the river. The situation is different from that in river-models in which the proper slope may be secured by increasing the discharge.

Two different methods of analysis indicate that friction- and shock-losses play an important part in determining the currents within the estuary. The energy transmitted into the estuary by the tidal wave is proportional to WLh^2, where W is the width of the channel, h is the tidal range, and L is the length the tidal wave would have if its velocity of advance were constant. For average conditions, this loss is about 75 per cent between the jetties and entrance to the river proper. Another rough calculation which can be made is loss of energy in friction within the estuary during each tidal cycle, which for average conditions is approximately 3×10^{12} ft/lbs per tide, while the energy transmitted into the estuary is of the order of 4×10^{12} ft/lbs per tide. These figures are in agreement with the loss of 75 per cent mentioned above. All of these computations require a number of approximations and the agreement should not be depended upon quantitatively, but the results indicate that hydraulic losses are extremely important.

The actual bottom-slopes within the estuary are relatively gradual and shock-losses resulting from sudden changes in area should not play an important part in nature, but in the model these slopes are greatly exaggerated and shock-losses will be relatively greater. For instance, in the model large vortices with vertical axes are observed in the lee of projecting points at which the bank is very steep. It is interesting to investigate the effect of pure shock-losses on the average slope of the energy-gradient, assuming that the same number of such losses occur in model and prototype in corresponding lengths. The slope is

$$KNv^2/\ell$$

where K is the loss-coefficient (assumed to be the same in model and nature), v is a representative velocity, N is the number of losses, and ℓ is the distance. The ratio of energy-slopes is then

$$b_s = b_v^2/b_e = b_z/b_x \tag{4}$$

However, the value of K depends upon the rate of change of area, which is greater in the model than in the prototype and consequently the loss by shock will be somewhat greater in the model than it should be to correspond to the distorted scale. Whether this excessive slope due to shock-losses will counterbalance the deficiency in skin-friction losses depends upon the nature of the model and the amount of distortion, and even when the two losses do compensate when averaged over the whole estuary, local discrepancies will certainly occur.

The most widely accepted theory of bed-load transportation relates this movement to the tractive force exerted on the bed. The average tractive force is related to the slope of the energy-gradient and the hydraulic radius by the equation

$$T = wRs \tag{5}$$

where T is the tractive force, w is the unit-weight, R is the hydraulic radius, and s is the slope of the energy-gradient. In wide channels or in narrow ones, in which the bottom is much rougher than the sides, R may be replaced by D, the average depth.

Replacing R by D and using Manning's equation for the slope of the energy-gradient

$$T = wn^2v^2/(1.49)^2D^{1/3} \tag{6}$$

$$b_T = b_n^2 b_v^2/b_z^{1/3} \tag{7}$$

Assuming the relation $b_v^2 = b_z$ to hold and that $b_n = 1$, $b_T = b_z^{2/3}$, which for the Columbia River model gives $b_T = 16$. In other words, the tractive forces in the model are roughly one-sixteenth those in nature. In nature, tractive forces range from 0.03 to 0.16 pound per square foot in the main channels.

The rate of bed-load motion has been represented by a number of formulae, the best known of which is that of Schoklitsch (Ueber Schleppkraft und Geschiebebewegung, Leipzig and Berlin, 1914)

$$G = \psi T(T - T_c) \tag{8}$$

where G is the rate of movement in pounds per second per foot of width, ψ is a coefficient which is nearly constant, and T_c is that tractive force below which no motion occurs. Starting from equation (8) and the various equations for T_c, one can obtain equations for the necessary size of material in the model. The results of these computations range from a reduction in size of material between $b_d = b_z^{4/7}$ and $b_d = b_z$, both of which appear to be impractical. Other lines of reasoning based on these and similar equations lead to the conclusion that the material in the model should have the same or nearly the same size as in nature. A. H. Gibson concluded both from theory and experiment that he should reduce his median diameter in the model of the Severn in the ratio 1:27.

This unsatisfactory state of our knowledge of bed-transportation complicates the design of river-models as well as those of estuaries and really leaves the selection of the vertical scale and size of sand to empirical methods. In the Columbia River model, the fixed banks were made vertical along the trace of mean high water so that changes in the vertical scale merely require the addition or removal of sand and a number of vertical scales and sands are to be tried.

One important complication resulting from the uncertainty regarding the size of the bed-material is that one is left without a time-scale for corresponding bed-movement. The time-interval corresponding to a tidal cycle is rather definitely fixed, but there is the possibility of altering the number of tides in a model year. Estimates based on the assumption that the size of sand is reduced so that the ratio of the actual tractive force to the critical value is the same in model and prototype indicate that the number of tides in a model year should be increased by factors ranging from $b_z^{3/14}$ to $b_z^{1/2}$. If, however, the ratio of the actual tractive force to the critical value is less in the model than in the prototype, an even greater increase in the number of tides will be required. Furthermore, if this condition is not fulfilled, the depths of scour in the model would be less than in nature.

Two other phenomena which affect the design of estuary-models are the formation of ripples and the angle of repose of sand under water. The conditions leading to the formation of excessively large ripples are not known and little can be done about them in advance. The angle of repose limits the distortion of the model and the minimum vertical reduction may be computed from the relationship

$$b_z = b_x(\tan 25°/\tan m) \tag{9}$$

where m is the maximum slope in nature. For the Columbia estuary, the minimum value of b_z to eliminate excessive slopes at all points is about 1000, but a scale-ratio of 200 will eliminate errors due to the angle of repose at all but a few points. The vertical scale to be used next will depend on the results of experiments now in progress using the 64 scale.

No measurements have been made of the annual amount of material moved into the estuary as bed-load. The amount fed into the model has been regulated so as to maintain in the river-channel above the estuary depths corresponding to those in nature. The average amount fed into the model corresponds to 29,000,000 tons per year in nature, when computed by the simple model-laws, and this figure appears reasonable in view of the estimated suspended load of 10,000,000 tons.

The average annual load of suspended material brought into the estuary by the Columbia River is 10,000,000 tons, which corresponds to an average deposit of 0.08 inch over the whole area inside the jetties. This material is brought down during the three months of the freshet-season and a large percentage of it is carried through the estuary. One feature of the representation of silt-deposits is that in distorted models the fall-velocity must be increased in the ratio $b_x/b_z^{3/2}$. For the Severn model, A. H. Gibson used sediment from nature and represented the flocculating action of sea-water by injecting alum. He thus increased the velocity of settling by a factor 2.7. Another method of representing this phenomenon is to use larger sediment having a greater settling velocity and to inject it into the river-channel just above the estuary proper.

The model-laws derived by Reynolds show that the tidal period should follow the relationship

$$b_t = b_x/b_z^{1/2} \tag{10}$$

However, if this ratio is followed, the friction-slopes are too small and the question arises as to whether better correspondence might not be attained by altering this period. If we consider a small basin in which tidal effects occur and which has a depth large in proportion to the range of tide, the velocity of the water entering at any instant is

$$v = (A/a)(dh/dt)$$

where A is the surface-area, a is the cross-sectional area, and h is the surface-elevation. If h may be represented by a function

$$h = f(nct - mx) \tag{11}$$

then

$$v = (nAc/a)f'(nct - mx) \tag{12}$$

If the function f is a sine or cosine, the period is

$$T = 2\pi/nc \tag{13}$$

For the conditions assumed, all velocities are increased in direct proportion to n which is inversely proportional to the period, provided that the velocity of advance c remains constant. Tidal waves are relatively long and flat and there is little reason to expect that c will be changed by a variation of n if the depths are not altered.

In addition to increasing all velocities, decreasing the tidal period from the value given by equation (10) increases all of the surface-slopes because the distance between any high water and the preceding or following low water is (1/2)cT and a reduction of T reduces the length and increases the slope. By decreasing the model-period, it may be possible to compensate for the proportionately low friction in the model in two ways, namely, the water-surface slopes are directly steepened, as explained, and the augmented velocities increase the friction-slope in the ratio n^2. If this modification of the model-law is permissible, it has the great advantage that all of the tractive forces are increased as n^2 and the rates of bed-movement to an even greater degree. The practical result will be that one can use a smaller vertical scale or, for a certain scale, can reduce the period of operation.

Large eddies with vertical axes formed behind points play an important part in the motion and it is important that the effect on them of a distorted tidal period be investigated. The equation for the surface-slope at any point is

$$gs = v^2/r \tag{14}$$

where r is the radius of curvature and s is the transverse-slope. If $b_v^2 = b_z$ and $b_r = b_x$, the conditions given by Reynolds' model-law, then $b_s = b_x^{-1} b_z$ and the local slope follows the scale of distortion. However, if v is increased in the ratio n, the ratios become

$$b_s = b_v^2 b_r^{-1} n^{-1} \tag{15}$$

and, if the slopes correspond to the distortion,

$$b_s = b_x^{-1} b = b \cdot b_r^{-1} n^{-1} \tag{16}$$

$$b_r = b_x n^{-1} \tag{17}$$

With distortion of the tidal period there is a tendency for the radius of curvature to be too large and this effect has been observed in experiments on the Columbia River model with the tidal period reduced from 99 to 60 seconds.

The advantages of a reduction of the tidal period are so great that a careful experimental study will be made of the various errors which may result from it. It should be pointed out that those estuary-models which are investigated by setting up steady flow through the model first in one direction and then in the other, have made a similar but even more radical assumption.

Distortion of the tidal period is not permissible when the water-velocity in nature is at or near the wave-velocity.

The Columbia River model includes a labyrinth to represent the tidal effect of the river

FIG. 1

above the estuary. The widths and bottom-elevations in the labyrinth correspond approximately to those in nature and the river-runoff is supplied above the end of tidal effects. This arrangement is believed to be superior to the use of inlet and outlet values at each end of the model because it requires control of elevation at one point only, whereas flowing water through the model requires control of two rates of flow and one elevation simultaneously, an almost impossible experimental situation if the period is short.

Adjustment of the labyrinth aims at the reproduction of the proper tidal prism and this result may be brought about by changing the depths to alter the velocity of advance of the tidal wave and adding resistance in the labyrinth to obtain the desired stage-discharge relationships.

Reproduction of wave-action is important near the ocean end of the estuary. Distortion of wave-heights and lengths in the same ratio as the other dimensions of the model is impossible and analysis shows it not to be desirable. If we adopt as the criterion for the size of waves the condition that the power transmitted by the waves be in the ratio $b_x b_z^{5/2}$, as given by the model-laws of Reynolds, then both the lengths and heights should be reproduced in the scale-ratio of vertical dimensions, b_z. This criterion appears to be reasonable in that the power transmitted by the waves is representative of their capacity to generate currents and produce other secondary effects.

Program of experiments

In spite of the fact that the scale-ratio of 64 involves very steep banks in the model, it has been used for the preliminary experiments because the velocities are large and the changes occur rapidly. As the preceding analysis of the model-laws shows, there are many uncertain factors which must be carefully investigated before the model can be used as a basis for designing improvements. Fortunately a great many measurements of currents have been made by means of current-meters and floats and frequent surveys are available over a long period. The preliminary experiments will include measurements of the effect of range and period of tide and size of sand on the currents, tidal prism, velocity of advance of tide, and scour and fill. Comparisons will be made between the results obtained under these conditions and those from the model and nature.

Following these preliminary experiments, a smaller vertical scale will be used and it is hoped that this second scale will show changes in the bed corresponding to those in nature. Should it be found impossible to reproduce the scour and fill with sufficient fidelity, the fixed bed will be constructed by molding the sand to present conditions and crusting the surface with cement. This fixed-bed model will then be used to investigate the effect of proposed works by measuring their effect on currents. This latter method is widely used with satisfactory results, but was not adopted for the Columbia model because it was thought desirable to investigate thoroughly the possibility of using a movable bed.

Work on the Columbia River model is being carried on by the United States Engineers under a cooperative agreement with the University of California. The laboratory is known unofficially as the United States Tidal Model Laboratory. Figure 1 shows the model-basin with the Columbia estuary-model in place. The ocean is in the background under the control-car and the river-

labyrinth is on the left. At the extreme right, a model of the Columbia River at Longview is under construction.

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A SEDIMENTATION-STUDY ON CLEARWATER RIVER, IDAHO

John P. Thomson

Introduction--Clearwater River is situated in north central Idaho and crosses the State from east to west. This major stream is unique in that it and all its tributaries rise and flow entirely in one state. The Clearwater's well-developed dendritic pattern is bounded on the north by the watershed of St. Joe River and on the south by the Salmon and its tributaries. Lewiston, Idaho, marks the point of confluence of Clearwater and Snake rivers. The Lewiston generating-station dam on Clearwater River is situated 2 miles from the River's mouth, near the eastern limits of the City of Lewiston. The total ponded area extends upstream for 3-1/2 miles. The area covered by that portion of the log-pond with which this paper deals extends 3000 feet upstream and covers 66 acres.

Clearwater River--This great River and its tributaries drain approximately 9500 square miles, or six million acres, in north central Idaho. Roughly, 7700 square miles are forest-land situated in the Selway, Clearwater, and Lolo National forests. About 480 square miles are either logged off or burned over.

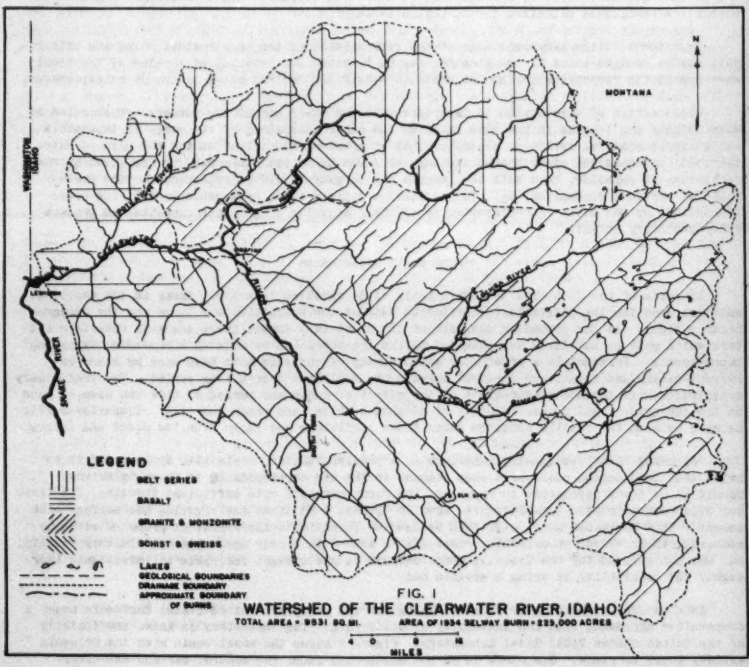


FIG. 1
WATERSHED OF THE CLEARWATER RIVER, IDAHO
TOTAL AREA = 9531 SQ. MI. AREA OF 1934 SELWAY BURN = 225,000 ACRES

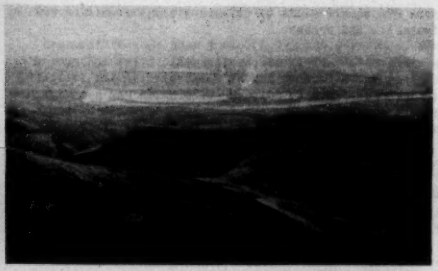


FIG. 2—GENERAL VIEW SHOWING LEWISTON GENERATING STATION DAM AND STORAGE RESERVOIR—CLEARWATER TIMBER COMPANY'S LOG-POND AND MILL

FIG. 3—LEWISTON GENERATING STATION DAM ON CLEARWATER RIVER

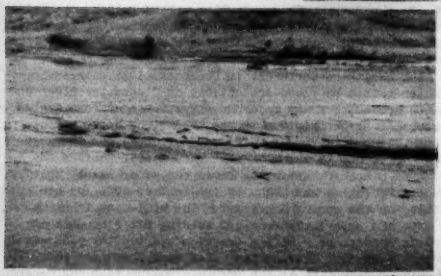


FIG. 4—UPPER END OF STORAGE-AREA, LEWISTON GENERATING STATION; ISLAND IN CENTER OF PICTURE WAS ERODED DURING FLOOD OF DECEMBER, 1933

FIG. 5—FOREGROUND SHOWING TYPE ALLUVIAL MATERIAL FOUND AT WATER'S EDGE UPPER END OF EMBAYMENT LEWISTON GENERATING STATION

The Clearwater watershed includes some 892 square miles of farm-land and a remaining 908 square miles is taken by grass-covered foothills and breaks.

The drainage-area of the Clearwater embraces a variety of physiographic types and geologic formations. The areal extent of formations in the watershed may be summarized in the following manner: Approximately 45 per cent of the drainage-basin is composed of granite and quartz monzonite of the Idaho batholith; 20 per cent is composed of the pre-Cambrian sediments of the Belt Series; 20 per cent is composed of the basalt of the Columbia Plateau; and 10 per cent is composed of schist and gneiss with a small remaining percentage in permian volcanics and tertiary andesite.

For the most part, the River's tributaries rise and flow through physiographic types and geologic formations similar to that of the main stream. In striking contrast, however, is the sharply incised canyon of Potlatch River which descends from the eastern margin of the Columbia Plateau to join the Clearwater 12 miles from Lewiston Pond. Potlatch River drains about 250 square miles of Palouse-type topography which supplies the fine-silt characteristic of the South Fork of Palouse River in Project 6 of the Soil Erosion Service.

The heaviest runoff on Clearwater River comes between April 15 and June 15 and is caused, for the most part, by melting snow. The lake-fed streams of the higher reaches of the drainage-basins carry little silt. The lower tributaries of the Clearwater drain a much different type of topography and surface-cover. These streams are often torrential and at flood-stage bring down great quantities of alluvium.

There are several factors which operate to determine the kind and amount of alluvium carried by the Clearwater. Normal supply of detrital materials from the watershed has been greatly disturbed by man's activity, particularly during the past ten years. Eighty thousand acres of unprotected slopes, bared by logging, and 225,000 acres burned off and burned out by the great Selway fire of August, 1934, have done much to change the nature of this historic stream.

The Lewiston Generating-Station Pond--The Inland Power and Light Company, predecessor to the Washington Water Power Company (the present owner), entered into an agreement with the Weyerhaeuser Timber Company whereby the power-corporation would build and maintain a pond in connection with their generating station in Clearwater River. This embayment was to be used as a mill-pond by the timber-company and kept at a minimum depth of five feet. Construction was completed in November, 1927, and water was admitted slowly until it was filled in February, 1928.

Flood of December, 1933--The rains that swept the Northwest in December, 1933, converted streams in many states into torrents. Water raised to flood-proportions on Clearwater River and on December 23 a crest-discharge of 163,000 second-feet was recorded. Systematic stream-gaging was first done in 1925 and the highest recorded stage previous to the 1933 flood was 112,000 second-feet. The flood damaged agricultural lands, railroads, highways, bridges, and the Washington Water Power Company's storage-area. Previous to the flood not enough silt entered the pond to endanger the contract with the timber-company. After the flood the water was so shallow that log-pond activity was impaired. Suction-dredging was begun in the fall of 1934 and has proceeded to the present shutdown, necessitated by the spring log-drive. The mill-pond is situated at the extreme lower end of the embayed area and apparently received nothing but fine silt and some water-logged drift in the form of roots and stumps. Before dredging started the pond was unwatered and a contour-map made of the silt-deposit. The map indicates that there are 253,777 cubic yards of silt in the pond. It is only of this part of the stream-alluvium that any record has been made. That sediment extends from the dam upstream 3-1/2 miles to the end of the ponded area can hardly be doubted. Alluvial material changes in size from the very fine sludge of the dredge-discharge to the heavy cobbles found at the upper end of the ponded area shown in the accompanying illustrations.

Maps and figures--Contour-maps of the pond and silt-deposit have been divided into areas of 100 square feet. The average depth of silt on every square was calculated, and the values were added to give the figure for total yardage. An isometric projection of the silt-deposit and a map of the Clearwater drainage-area were made. The watershed-map indicates approximate geologic formation-boundaries and areas of burned-over districts. A few photographs are included to show details at specific localities.

Conclusion--Clearwater River, so named in pioneer times because of its uniformly clear water, supplies the Lewiston generating-station pond.

Six years after completion, a portion of this storage- and mill-reservoir had to be dredged

to remove silt for proper log-flotation.

Comparative maps show that 253,777 cubic yards of silt have been deposited. These maps cover but 66 acres at the extreme lower end of the 780-acre ponded area.

Soil Conservation Service,
U. S. Department of Agriculture,
Pullman, Washington

A STATE-WIDE PROGRAM OF PERIODIC MEASUREMENTS OF GROUND-WATER LEVEL IN NEBRASKA

L. K. Wenzel

The precipitation in Nebraska has been considerably less than normal in the last four years, and in consequence the ground-water level in many parts of the State has declined to a marked extent. Moreover, in some parts of Nebraska the ground-water level has declined as the result of land-drainage, and in other parts it has risen as the result of irrigation with water diverted from streams. These changes in ground-water level produced by drainage, irrigation, and decreased precipitation have caused wells to fail, streams to cease flowing, lakes to become dry, and land to become water-logged. Consequently, interest in fluctuations of ground-water level has greatly increased, and the need of a systematic collection of base-data for the future study of ground-water problems has been recognized.

The water-levels in about 60 observation-wells in the Platte River Valley have been measured periodically since 1930 as a part of an investigation of the ground-water resources of south-central Nebraska by the United States Geological Survey in cooperation with the Conservation and Survey Division of the University of Nebraska. In 1934, a state-wide program of measurements of ground-water level was begun as the result of the increased interest in this subject, and the measurements on the wells in the Platte Valley were continued as a part of that investigation.

The state-wide program consists of periodic measurements of the water-levels in selected observation-wells and the collection of related data on factors that influence the fluctuations of the water-levels. At the present time measurements are being made chiefly on observation-wells that are located in areas unaffected by heavy withdrawals, but it is planned to increase the scope of the program to include observations on the water-levels in areas where heavy withdrawals are being made, such as the vicinity of municipal pumping-plants.

In all, about 350 wells were selected, including the previously mentioned wells in the Platte River Valley and a group of wells that are being measured by the United States Biological Survey. These wells are distributed over the 77,000 square miles of the State (see Fig. 1). Abandoned wells were selected wherever possible, because the water-levels in such wells reflect natural fluctuations. However, in some parts of the State abandoned wells could not be found, and in these areas pumped wells were selected, or wells were drilled specifically for purposes of observation. It is planned in the future to substitute other more satisfactory wells for the pumped wells.

The observation-wells were located in as many different climatic, geologic, and topographic situations as possible, in order that all types of water-level fluctuations could be observed and studied. The wells are distributed over the four major ground-water provinces of the State--the glacial-drift area of eastern Nebraska, the loess-hills and plains of south-central Nebraska, the sand-hills of northern and central Nebraska, and the Tertiary plains of western Nebraska. Many of the wells are located in the valleys of the streams, and it is hoped that the relation between the ground-water level and the flow of streams can be studied as a part of this program. About 90 of the wells are located in the valley of the Platte River, the principal stream of Nebraska, along its 400-mile course in the State. There are also wells in the valleys of the Republican, White, Niobrara, Elkhorn, Little Blue, Big Blue, and Nemaha rivers. A few wells have been located in the valley of Lodgepole Creek, in western Nebraska, to observe the ground-water level fluctuations in the valley of an interrupted stream--that is, a stream that flows in certain stretches of its course and is dry in intervening stretches. Wells have also been located in the valleys of streams near points where the visible flows begin or end, in order to study the changes in the flowing lengths of the streams. Some wells have been located in the valleys of streams and others nearby on the uplands, in order that the fluctuation of the water-levels in the valleys and on the uplands might be compared. Two lines of wells extending from the Platte Valley northward into the sand-hills were installed in order to observe the effects of

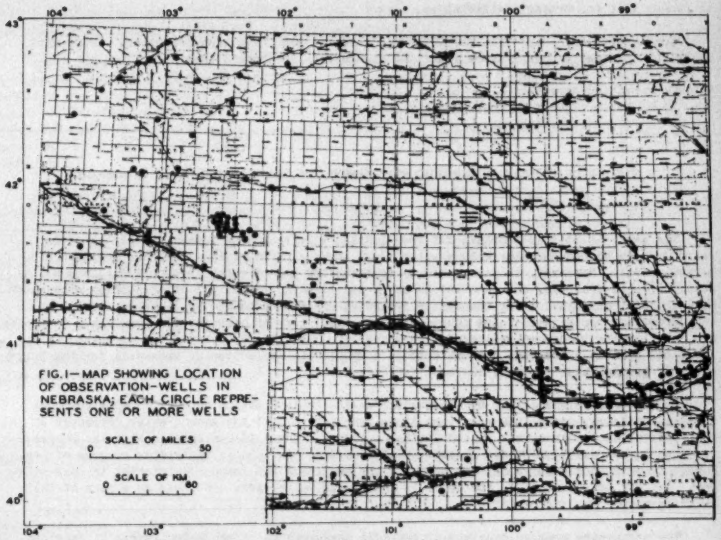


FIG. 1—MAP SHOWING LOCATION OF OBSERVATION-WELLS IN NEBRASKA; EACH CIRCLE REPRESENTS ONE OR MORE WELLS

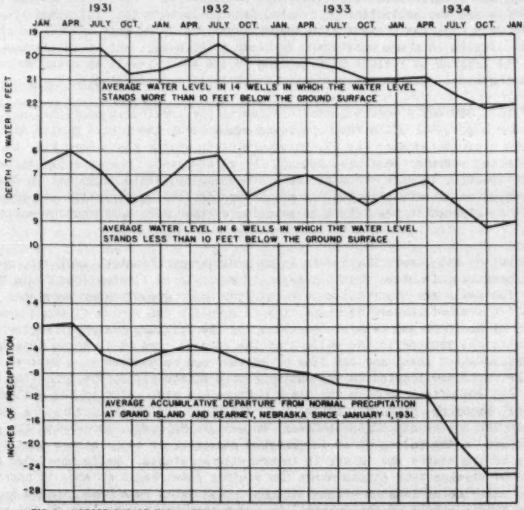
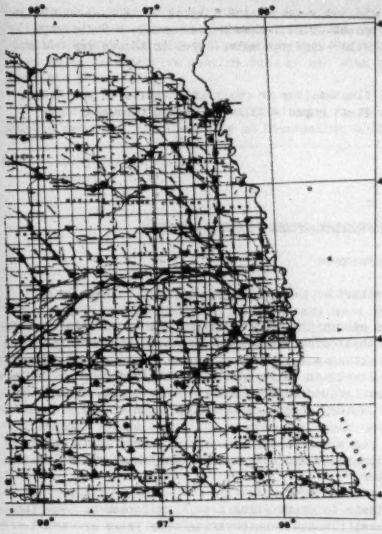


FIG. 2—HYDROGRAPHS OF THE AVERAGE WATER LEVELS IN OBSERVATION WELLS LOCATED IN THE PLATTE VALLEY BETWEEN GRAND ISLAND AND KEARNEY, NEBRASKA, AND THE ACCUMULATIVE DEPARTURE FROM NORMAL PRECIPITATION SINCE JANUARY 1, 1931 RECORDED AT STATIONS OF THE U. S. WEATHER BUREAU AT GRAND ISLAND AND KEARNEY



ground-water percolation on fluctuations of the water-level. Many wells have been located on the upland plains, where the water-level lies relatively far below the land-surface.

The water-levels in the observation-wells in Nebraska range from less than one foot to more than 275 feet below the land-surface. In general, they are deepest in western Nebraska and decrease in depth toward the east. The water-levels are, of course, generally deepest on the uplands and shallowest in the valleys, except possibly in the glaciated area of eastern Nebraska, where the water-level is comparatively shallow on many of the hilltops. It is hoped that this program will provide data for a study of the effect of the depth to the water-level on recharge from precipitation.

Measurements of the water-levels in the observation-wells have been made about once a month since the location of the wells was completed in the fall of last year. The wells are measured by H. A. Waite of the Conservation and Survey Division of the University of Nebraska. The route followed to reach all the wells necessitates crossing the State several times and covering a total distance of about 5000 miles. Automatic water-stage recorders are to be installed on several of the wells, in order that more detailed records may be had of the fluctuation of the water-level in certain areas.

No important conclusions can yet be drawn from the wells that have been measured only since 1934. In general, most wells in the stream-valleys, where the water-levels are comparatively shallow, have recovered considerably from their low levels of last fall, whereas wells on the uplands have shown very little change.

About 20 of the observation-wells, on which periodic measurements have been made since 1930, are located in the part of the Platte Valley between Grand Island and Kearney, where the water-table stands from about 2 to 30 feet below the land-surface. For the purpose of study, the wells were divided into two groups--one consisting of wells in which the water-level stands more than 10 feet below the ground-surface and the other consisting of wells in which it stands less than 10 feet below the ground-surface. The water-levels in the observation-wells of each group were averaged, and the average fluctuations for the period 1930 to 1934 were plotted, together with the accumulative departure from normal precipitation, in Figure 2.

The water-levels in the wells of the second group (with shallow water-level) in general rise and fall more than those in the wells of the first group. This more active fluctuation is due to the following causes: Recharge from precipitation occurs more frequently where the water-table is shallow and thus larger rises of the water-level result. On the other hand, the roots of more plants draw water directly from the zone of saturation where the water-table is shallow, and consequently larger declines of the water-level occur in the growing season. In the winter and spring of 1931, 1933, and 1934 the average rise was less than one inch in the wells with deeper water-level but more than one foot in the wells with shallow water-level. The decline in the summer and fall was likewise greatest in the shallow-water wells. Consequently in the last four years the net decline was nearly the same in the two groups.

In the first half of 1932 there were rather large rises of the water-levels in all the wells in the Platte Valley. The cause of this rise is apparent from the curve showing accumulative departure from normal precipitation. From October 1931 to April 1932 the average precipitation recorded at Grand Island and at Kearney was slightly above normal, and consequently considerable water percolated into the ground and was added to the ground-water reservoir in this

recharge-period. As a result the water-level did not reach as low a level in 1932 as it did in 1931. Since July 1932 the precipitation has been about 22 inches below normal--a deficiency equivalent to almost one year's normal precipitation--and the water-level in the Valley has suffered annual net declines.

The graphs showing the 4-year water-level fluctuations in observation-wells in the Platte Valley illustrate the type of information that it is hoped will be collected throughout the State by the present program.

U. S. Geological Survey,
Washington, D. C.

THE NEED FOR A NATION-WIDE PROGRAM OF OBSERVATION-WELLS

O. E. Meinzer

(Abstract)

During the severe droughts of recent years almost the only water-supplies available throughout large areas of the United States have been those obtained from underground sources. Consequently, a great interest has developed in the ground-water resources of the country and there has been much concern lest the declining water-levels in wells and the diminished flow of springs may be warnings of the ultimate exhaustion of our ground-water supplies. As is well known, the United States Geological Survey has for half a century conducted investigations of the ground-waters of the country and numerous investigations have been made by State geological surveys and other agencies. However, the time is now ripe for a coordinated, continuing program to obtain systematic records of water-levels in observation-wells and correlative records of natural discharge and artificial withdrawals of ground-water.

The records of water-levels in wells and their interpretation have long formed an important part of ground-water work. Records of water-level fluctuations covering many years are available for a few areas, as in southern California, Honolulu, the Roswell Basin in New Mexico, and Long Island; and records covering shorter periods are available for other areas of heavy ground-water withdrawal, such as areas in New Jersey and Florida; Memphis, Tennessee; the rice-districts of Arkansas; the Houston and Winter Garden areas in Texas; the Platte Valley in Nebraska; the Salt Lake and Ogden areas in Utah; the Mimbres and Portales valleys in New Mexico; the Salt and Gila valleys in Arizona; and certain areas in California, Idaho, and other States. On January 1, 1933, about 3000 observation-wells in the country were being measured periodically by the Ground Water Division of the United States Geological Survey or by cooperating parties, of which about 115 were equipped with automatic water-stage recorders. The large majority of these wells were in areas of heavy withdrawal.

It has long been realized that more observation-wells ought to be established in areas outside of the intensively developed areas in order to obtain information as to the fluctuation of ground-water levels due to natural causes and to such general artificial causes as that of bringing under cultivation virgin timber- and prairie-lands. A water-stage recorder on a well in an area unaffected by pumping several miles from Runyon, New Jersey, has been operated since 1923, and a water-stage recorder on a similar well in Virginia, near Washington, D. C., has been operated since 1928. The records of these wells became very valuable in connection with the drought of 1930. About that time measurements of water-levels were begun in observation-wells remote from intensively developed areas in several other States, as for example in Maryland, Pennsylvania, North Carolina, and Nebraska. Within the last year several additional programs, including an aggregate of several hundred observation-wells, have been started in areas not affected by heavy pumping, the largest of which is in cooperation with the United States Soil Conservation Service and includes wells in North Carolina, South Carolina, Wisconsin, Iowa, Missouri, Kansas, Oklahoma, Texas, and Washington. The others are in cooperation with State organizations, chiefly the State Water Commission of Connecticut and the State geological surveys in Michigan and Nebraska.

The immediate problem is to round out this work into a comprehensive and coordinated national program, to place it on a thoroughly sound technical basis, and to provide for its orderly and effective continuation. In an endeavor to bring nearer to realization a nation-wide program, the writer, on October 15, 1934, appointed a Committee on Observation-Wells, consisting of seven members of the Ground Water Division of the United States Geological Survey, with R. M. Leggette, chairman, and L. K. Wenzel, secretary. This Committee has been actively at work and

has held weekly meetings for discussion, with the result that its comprehensive and detailed report is now approaching completion. It has become evident that the entire subject is a highly technical one, as to both the obtaining and the interpreting of the records, and that the work if it is to be effective must be done by men with specialized technical training or under their immediate supervision.

[This paper, in slightly modified form, is to be issued as an introduction to the mimeographed Report of the Committee on Observation-Wells of the United States Geological Survey.]

U. S. Geological Survey,
Washington, D. C.

FURTHER TESTS OF PERMEABILITY WITH LOW HYDRAULIC GRADIENTS

V. C. Fishel

Many of the water-bearing formations in the United States have hydraulic gradients of much less than 20 feet to the mile, and some may have gradients of less than one foot to the mile, whereas most laboratory-tests of permeability are made with much higher gradients. An investigation was therefore undertaken by the writer, under the direction of O. E. Meinzer, in the Hydrologic Laboratory of the United States Geological Survey, to determine whether Darcy's law is valid for very low hydraulic gradients--that is, whether under such low gradients the rate of flow remains proportional to the gradient. In a previous paper by Meinzer and the writer (Amer. Geophysical Union, 15th annual meeting, pp. 405-409, 1934), it was shown that for the sand tested the rate of flow varies directly with the hydraulic gradient down to a gradient of about one foot to the mile. More recently six additional tests have been made on this sand with the same apparatus, and these tests give evidence of the validity of Darcy's law for still lower gradients.

Procedure of test--The apparatus used and the procedure followed in making the tests were fully described in the paper cited. The procedure in making the test is essentially as follows: The saturated material to be tested is placed in a long U-tube apparatus and covered in both tubes with a short column of water. The test is started with the water-level in one column at any desired height above the water-level in the other column. As the water flows through the sample the higher water-level declines and the lower water-level rises, with the result that the head which causes the flow diminishes continuously but at a decreasing rate. The only observations that are required are the differences in the water-levels at stated times, the quantities of flow during the intervals between successive observations being computed from the changes in water-levels and the cross-section area of the tubes.

Method of expressing the results--For the purpose of this study the results may be expressed as the volume-rate of flow through the material to be tested or as a coefficient of permeability. The volume-rate of flow for any interval of time can be computed from the following formula, as the two columns of water have the same area:

$$R = 1000\ A(h_1 - h_2)/2t$$

Table 1--Results of test 10

No.	Date	Time	Observed head	Hydraulic gradient	Permeability-coefficient	Rate of flow	Computed head
	1934	h m	mm	ft/mi		mg/sec	mm
1	June 1	10 47	3.190	8.42	...	.....	3.1790
2	1	16 25	2.300	6.07	320	0.0616	2.3120
3	1	22 25	1.635	4.32	313	0.0432	1.6470
4	2	8 00	0.971	2.56	300	0.0270	0.9582
5	2	11 40	0.783	2.07	323	0.01998	0.7792
6	2	23 15	0.398	1.05	322	0.01296	0.4047
7	3	12 15	0.205	0.54	282	0.00579	0.1941
8	3	18 30	0.138	0.36	349	0.00418	0.1363
9	3	22 50	0.110	0.29	289	0.00252	0.1067
10	4	8 00	0.072	0.19	256	0.00161	0.0636
11	4	14 45	0.038	0.10	510	0.00193	0.0434
12	4	22 25	0.015	0.04	658	0.00117	0.0282
13	5	8 20	0.015	0.04	...	0.0000	0.0160

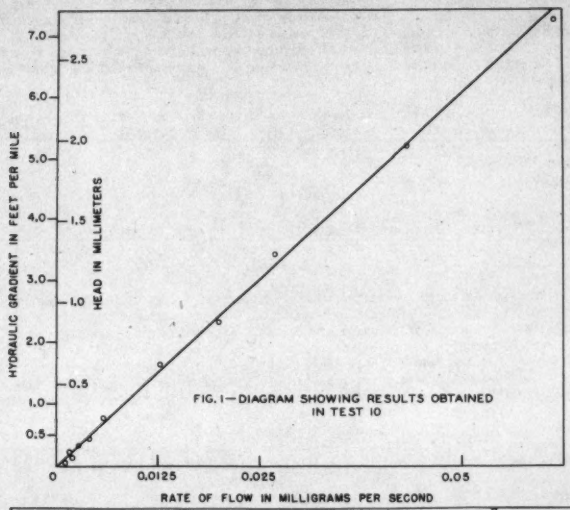


FIG. 1—DIAGRAM SHOWING RESULTS OBTAINED IN TEST 10

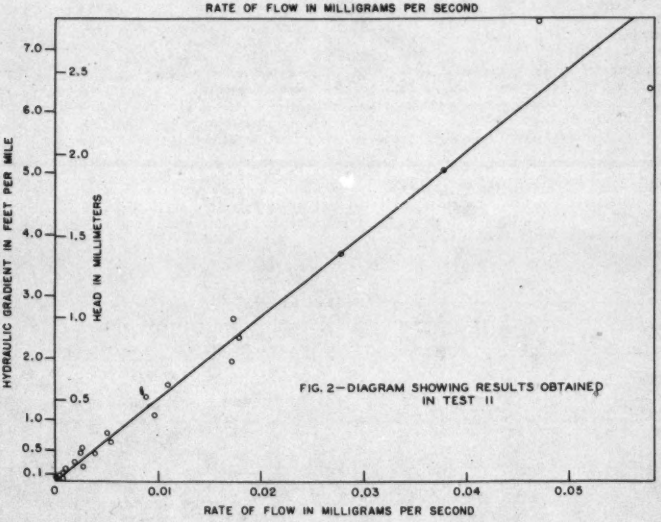


FIG. 2—DIAGRAM SHOWING RESULTS OBTAINED IN TEST 11

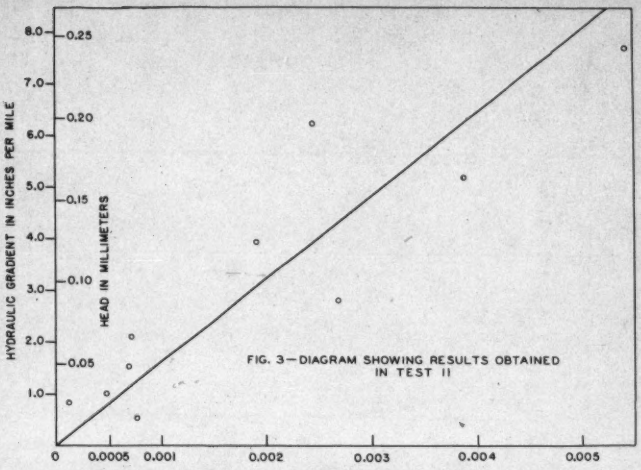


FIG. 3—DIAGRAM SHOWING RESULTS OBTAINED IN TEST 11

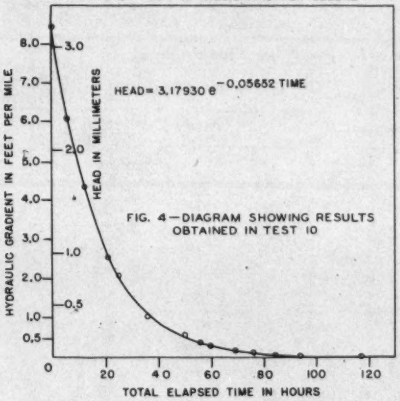


FIG. 4—DIAGRAM SHOWING RESULTS OBTAINED IN TEST 10

In the above formula, R is the volume-rate of flow through the material, in milligrams per second, A is the cross-sectional area of the tubes and is equal to 28.076 square centimeters, h_1 and h_2 are the respective differences in water-levels, in centimeters, and t is the interval of time, in seconds.

The coefficient of permeability that is used in the Hydrologic Laboratory is expressed by the rate of flow, in gallons a day, through a square foot of the cross-section of the material tested, under a hydraulic gradient of 100 per cent at a temperature of 60° F. The permeability of a material tested in the apparatus that was used can be computed by the formula

$$P = (K/t) \log_{10} (h_1/h_2)$$

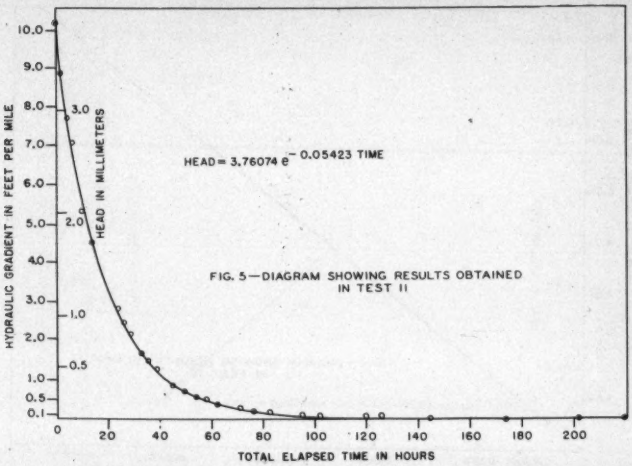


FIG. 5—DIAGRAM SHOWING RESULTS OBTAINED IN TEST 11

in which P is the coefficient of permeability and K is a constant depending on the apparatus and the units used. In these tests K = 45,782,000. The temperature remained constant, and therefore no temperature-correction was necessary for the purpose of this study. The results obtained in tests 10 and 11 are shown in Tables 1 and 2 and in Figures 1 to 5.

Table 2--Results of test 11

No.	Date	Time	Observed head	Hydraulic gradient	Permeability-coefficient	Rate of flow	Computed head
	1934	h m	mm	ft/mi		mg/sec	mm
1	June 8	8 56	3.850	10.16	...	.....	3.7607
2	8	10 50	3.355	8.86	398	0.1016	3.3925
3	8	13 15	2.931	7.74	329	0.0735	2.9769
4	8	15 15	2.690	7.10	238	0.0470	2.6709
5	8	19 05	2.097	5.54	358	0.0603	2.1688
6	8	23 00	1.719	4.54	280	0.03765	1.7545
7	9	8 15	1.063	2.81	284	0.02764	1.0624
8	9	11 00	0.940	2.48	247	0.01745	0.9137
9	9	13 15	0.822	2.17	325	0.02045	0.8101
10	9	17 25	0.639	1.69	333	0.01711	0.6461
11	9	20 25	0.555	1.47	257	0.01091	0.5491
12	9	24 00	0.475	1.25	239	0.00870	0.4522
13	10	5 40	0.336	0.89	338	0.00958	0.3325
14	10	10 30	0.274	0.72	232	0.00500	0.2559
15	10	15 05	0.210	0.55	320	0.00544	0.1995
16	10	19 05	0.185	0.49	174	0.00244	0.1606
17	10	23 00	0.146	0.39	331	0.00388	0.1299
18	11	8 00	0.102	0.27	219	0.00191	0.0797
19	11	13 10	0.074	0.20	336	0.00269	0.0602
20	11	19 25	0.059	0.16	203	0.000960	0.0429
21	12	8 30	0.036	0.10	210	0.000692	0.0211
22	12	15 00	0.028	0.07	204	0.000462	0.0148
23	13	8 30	0.023	0.06	62	0.000113	0.0057
24	13	15 00	0.010	0.03	687	0.000772	0.0040

If the rate of flow is proportional to the gradient, in accordance with Darcy's law, an exponential curve will result when the total elapsed time is plotted against the head. It can be

shown that this curve follows Darcy's law by obtaining a number of ordinates and their respective abscissas from the curve and substituting these figures in the formula for the coefficient of permeability.

In the two examples given in Figures 4 and 5 the equation of the curve was computed by the method of least squares from the observed heads and their respective total elapsed times. The curve was drawn to fit this equation, and the observed heads, which are represented by small circles, were then drawn in their respective positions corresponding to the correct time-interval. The computed heads shown in Tables 1 and 2 were computed from the equation of the curve. The difference between the observed and computed heads is the error of observation. The probable error of a single observation is given by the following standard formula:

$$r = 0.6745 \sqrt{\Sigma[h_o(h_o - h_c)^2]/(n - 1)}$$

in which r is the probable error of a single observation, h_o and h_c are the observed and computed heads, respectively, and n is the number of observations. The probable error of a single observation in tests 10 and 11 was 0.007 and 0.033 millimetr, respectively. When the stage is reached in which the gradient is very low, the changes in head for any given period become much smaller, and consequently the errors in determining the head produce large irregularities in the computed coefficients. However, no progressive departure from the curves is shown even for extremely low gradients.

Conclusions--The observations of tests 10 and 11 fall within the range of the probable error of an observation for gradients of less than one inch to the mile. The results of these tests show rather conclusively that for the material tested the rate of flow varies directly as the hydraulic gradient, down to a gradient of two or three inches to the mile, and there are indications that Darcy's law holds for indefinitely low gradients.

U. S. Geological Survey,
Washington, D. C.

GROUND-WATER STUDIES IN THE HUMID AND SEMIARID PARTS OF THE TEXAS COASTAL PLAIN

S. F. Turner and Penn Livingston

The sediments that underlie the Texas Coastal Plain have a thickness of many thousand feet and consist largely of shale and clay interbedded with sandstone and sand. Except in localities where there are notable folds or faults, the beds have a dip to the east or southeast materially steeper than the slope of the present land-surface, and formations that crop out in the northern part of the Coastal Plain occur at depths of several thousand feet at the present coast line. The geologic structure, therefore, as well as the arrangement and texture of the beds, is favorable for the intake and accumulation of stores of ground-water in the permeable sands.

The underground reservoirs in these sands are chiefly replenished by the penetration of rain that falls on the outcrop. Some water is contributed by seepage from streams, but in most places the beds of the streams are sealed by deposits of clay or silt.

Outstanding water-bearing formations of the Texas Coastal Plain are the Carrizo Sand, the Goliad Sand, and the Lissie Formation. The outcrops of these formations in a part of the State are shown on Figure 1.

The largest development of water from the Carrizo Sand has been made in Dimmit and Zavala counties, in the Winter Garden District of southwestern Texas, and the largest development from the Goliad Sand and Lissie Formation has been made in the Houston-Galveston District and in several counties that are closely adjacent to that district in southeastern Texas. Comprehensive investigations of ground-water in these two districts and in other parts of the Texas Coastal Plain have been made by the United States Geological Survey in cooperation with the Texas Board of Water Engineers. These investigations have been made under the direction of Walter N. White of the Geological Survey. Interesting comparisons regarding the conditions that control the amount of the available supplies of ground-water can be drawn from the results of these studies.

The center of the Winter Garden Area is at Carrizo Springs, about 100 miles southwest of San Antonio. The climate in this part of Texas is semiarid, the average annual rainfall amounting to about 20 inches, and irrigation is necessary to insure a crop. For many years after settlement the principal industry was stock-raising, but about 1890 artesian water was discovered

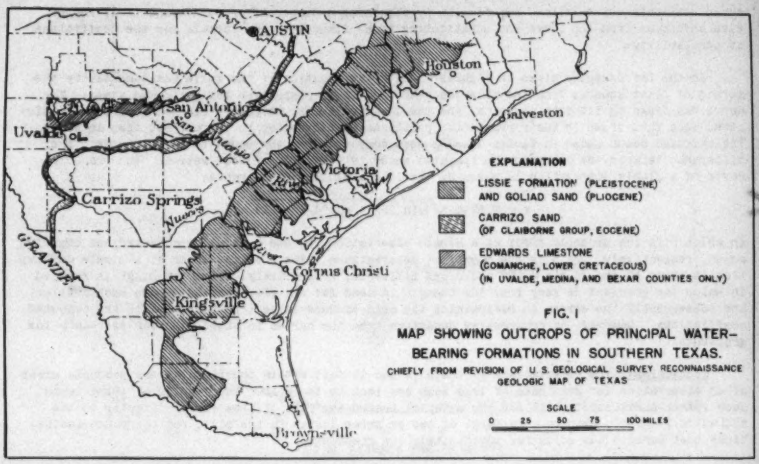


FIG. 1

MAP SHOWING OUTCROPS OF PRINCIPAL WATER-BEARING FORMATIONS IN SOUTHERN TEXAS.

CHIEFLY FROM REVISION OF U. S. GEOLOGICAL SURVEY RECONNAISSANCE GEOLOGIC MAP OF TEXAS

by well-exploration in the Carrizo Sand, and since then there has been a gradual transition to irrigation-farming and the production of winter fruits and vegetables.

The investigation in this area was started in the fall of 1929 by T. W. Robinson and S. F. Turner. At that time about 27,000 acres were irrigated with water from about 500 pumped and flowing wells in Dimmit and Zavala counties, all of which derived their water from the Carrizo Sand. For years prior to the start of the investigation the water-level in these wells had persistently fallen until in some of the wells that once had a flow the static level stood about 100 feet below the surface, and the pumping lift in some localities had reached 200 feet or more. This was close to the economic pumping limit for the crops irrigated under prevailing prices, and some of the well-owners became alarmed lest the water-supply was about to fail.

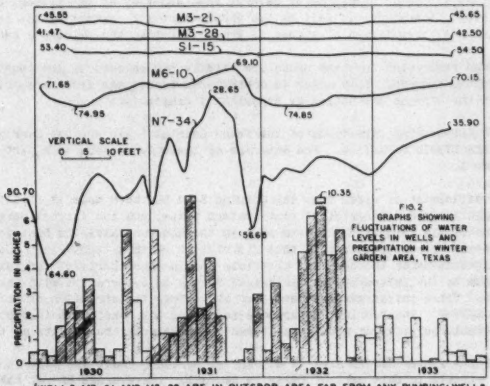


FIG. 2

GRAPHS SHOWING FLUCTUATIONS OF WATER LEVELS IN WELLS AND PRECIPITATION IN WINTER GARDEN AREA, TEXAS

(WELLS M3-21 AND M3-28 ARE IN OUTCROP-AREA FAR FROM ANY PUMPING; WELLS S1-15 AND M6-10 ARE IN OUTCROP-AREA NEAR PUMPING; AND WELL N7-34 IS AN ARTESIAN WELL NEAR CENTER OF LARGEST PUMPING DISTRICT)

Some of the outstanding conclusions reached in the investigation are as follows: The outcrop area of the Carrizo Sand that supplies water to the wells of Dimmit and Zavala counties covers about 175,000 acres. Most of the water supplied to the sand comes from rainfall on the outcrop area, only a minor part coming from the streams that cross the outcrop. The principal penetration of rainwater into the Carrizo Sand occurs during years of heavy rainfall on the parts of the outcrop area where the soil is very sandy, there being comparatively little penetration in the years of light rainfall.

The water moves by percolation from the outcrop to the pumped districts. The estimated flow is about 24,000,000 gallons a day. This estimate is based on the average thickness of the Sand as shown by well-logs, on the average coefficient of permeability determined by the pumping tests and laboratory-tests of sand-samples, and on the average hydraulic gradient determined by leveling and water-level measurements.

In the outcrop area the water-table generally displayed only a small amount of seasonal variation, including a small rise in some of the wells after heavy rains. In most of the outcrop-area there was little net change from 1929 to 1933, but in two localities of considerable size on the outcrop the water-level declined one-half foot to 5 feet. One of these areas is being pumped rather heavily; the other is close to an area of heavy pumping (see Fig. 2). In areas down the dip where the water is under artesian pressure and most of the pumping is done, there were large seasonal fluctuations in the water-levels, but the levels in nearly all the observation-wells held their own or were higher at the end of the period than at the beginning. The average annual pumpage during the three seasons 1929-30 to 1932-33 probably was slightly less than 20,000 acre-feet. It was concluded that the supply of water which it is safe to withdraw from wells in the Carrizo Sand in Dimmit and Zavala counties amounts to about 20,000 acre-feet a year. One of the most significant facts disclosed is that in the outcrop-area the underground reservoir is not filled, and some unwatering took place during the period of the investigation.

The ground-water resources of the Houston-Galveston Area, comprising Harris County and parts of adjoining counties, have been the subject of an intensive study since 1930 by W. N. White, Penn Livingston, and S. F. Turner. Houston and Galveston and adjacent industrial areas obtain public and industrial water-supplies entirely from wells. The climate of the area is humid, the average annual rainfall at Houston amounting to about 45 inches, and most crops can be matured without irrigation. Rice, however, requires heavy irrigation, and large quantities of well-water are used for this purpose. In practically all parts of the area where the withdrawals have been heavy the head in flowing wells has declined and the water-levels in non-flowing wells have fallen. In some localities the decline prior to 1930 amounted to 100 feet or more, and it became a matter of public concern lest the decline should continue until it would no longer be feasible to pump the wells or the wells should become contaminated by salt water.

Some of the outstanding conclusions reached from the investigation in this area are as follows: The largest developed supplies of ground-water in the area, including most of the Houston supplies, come from sands in the Goliad Sand and Lissie Formation. The very large outcrop-areas of these sands lie north of Houston.

Most of the time on the greater part of the outcrop areas there is both a true water-table and a perched water-table (see Fig. 3). The permeable sandy soils and sandy loam-soils are underlain by silty sand or sand mixed with some clay, which usually are somewhat less permeable than the soils. The soils readily absorb the rain, and the water moves downward in them at a comparatively rapid rate. When it reaches the underlying silty or clayey sands its movement becomes slower, and as a result these materials become saturated. During the summer practically all the moisture that penetrates the soils is dissipated by evaporation and by transpiration of grasses, shrubs, and trees. During the late fall, winter, and spring, however, the evaporation- and transpiration-losses are small, and a temporary perched water-table is built up.

During the winter of 1931-32 there was a substantial rise in the water-levels of all the 70 observation-wells on the outcrop-areas of the Goliad and Lissie, both those that are believed to penetrate to the true water-table and those that are believed to penetrate only to perched water. The rise in the water-table wells was much less than the rise in the perched-water wells and showed considerable lag (see Fig. 3). Apparently the perched water is slowly but continuously moving downward to the true water-table. The lysimeter-experiments undertaken in this area were only partly successful, but they indicate that water in the perched zone moves downward toward the water-table. Large quantities of perched water are discharged into the streams of the outcrop through springs.

Most of the water withdrawn from the underground reservoirs in Harris County is supplied by

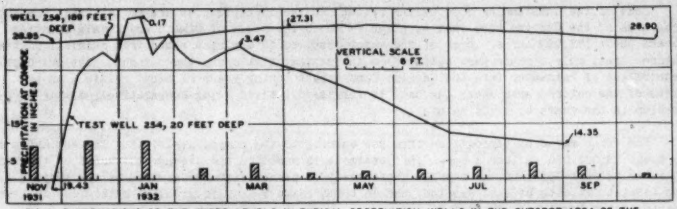


FIG. 3—FLUCTUATIONS OF THE WATER-LEVELS IN TYPICAL OBSERVATION-WELLS IN THE OUTCROP-AREA OF THE GOLIAD SAND AND LISSIE FORMATION NORTHWEST OF HOUSTON, TEXAS, AND PRECIPITATION AT CONROE, TEXAS (WELL HIT-3 IS PROBABLY A TRUE WATER-TABLE WELL UNAFFECTED BY PUMPING AND TEST-WELL NUMBER 1 IS A PERCHED WATER-TABLE 100 FEET AWAY FROM IT)

percolation from the outcrops to the pumped district. In the greater part of the area the water is moving from northwest to southeast, which is the direction of both the hydraulic gradient and the slope of the land. A depression in the artesian head has been created by the withdrawals of water in the areas of greatest pumping development, located within the city limits of Houston and in an area in the vicinity of Pasadena, a short distance to the southeastward.

A tentative estimate of the inflow toward the Houston District gives about 45,000,000 gallons a day. In reaching this estimate it was assumed that the inflow passes through a vertical section of the sandstone 50 miles long along the 20-foot contour above sea-level of the artesian surface as mapped in 1931 and that along this contour the average thickness of the water-bearing beds is 600 feet, the average coefficient of permeability is 150, and the average hydraulic gradient is 10 feet to the mile.

The figures computed as the average pumpage from all public and private wells in the 150 square miles of the Houston District were 52,000,000 gallons a day in 1930 and 50,000,000 gallons a day in 1931, and the estimated figure for 1932 was only slightly less than that for 1930. In most of the observation-wells of the area the water-levels either held their own or were higher in 1933 than they were in corresponding months of 1931 (see Fig. 4). The significant fact was brought out, therefore, that on the average the artesian head rose in the heavily pumped districts during 1931 and 1932, although the pumpage in those districts was not very much below that of 1930. The conclusion was reached that the underground reservoir is capable of supplying more water for the Houston District than had been withdrawn from it before 1933.

A somewhat intensive ground-water investigation has recently been made in Kleberg County, of which Kingsville is the county-seat, in the semiarid part of the Coastal Plain. A report by Penn Livingston and T. W. Bridges, giving the results of the investigation, has been completed and is awaiting publication. In this county most of the sands of the Goliad Sand and Lissie

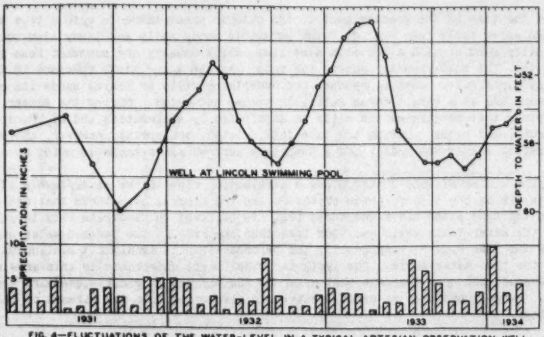


FIG. 4—FLUCTUATIONS OF THE WATER-LEVEL IN A TYPICAL ARTESIAN OBSERVATION-WELL AND PRECIPITATION AT HOUSTON, TEXAS

Formation contain brackish or salty water, and the average thickness of the sands that contain fresh water does not exceed about 150 feet. Largely on this account the available supplies of potable water are very much less than they are in the Houston District. Probably they are not much larger than is required to supply the domestic and industrial needs of Kingsville and the stock and domestic requirements of the farms and ranches of the county.

Significant comparisons can be drawn from the studies of these three areas. In the Winter Garden District some of the wells are close to the outcrop of the Carrizo Sand or on the outcrop itself. The underground reservoir of the outcrop is not filled, and some unwatering is taking place. There the available supply is largely determined by the amount of the average annual recharge from rains, which is not very great, because the outcrop area is small and the rainfall is relatively scanty. The wells of the Houston District are remote from the outcrop of the water-bearing sands, and the available supply is determined largely by the capacity of the sands to transmit water from the outcrop to the wells, regardless of the amount of the annual recharge on the outcrop, which presumably is relatively large--in fact, the reservoir on the outcrop apparently is spilling into the streams. In Kleberg County the wells are also remote from the outcrop and the transmission-capacity of the sands is the governing factor. The transmission-capacity is small, however, because the fresh-water sands are comparatively thin. In this area it appears probable that the salt water which entered the sands of the Goliad and Lissie when they were deposited has been flushed out to a lesser extent than in the Houston area. This may have been due to several causes, of which the aridity of the climate is one.

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EVAPORATION FROM LARGE WATER-SURFACES BASED ON RECORDS IN CALIFORNIA AND NEVADA

S. T. Harding

Much work has been done on measurements of evaporation from tanks and the coefficients which should be used to reduce such tank-observations to the evaporation from large water-surfaces. This work has made available fairly dependable methods and records from which the probable evaporation from large water-surfaces in nearly all areas can be estimated as closely as may be essential in most water-supply studies. However, all such methods involve factors of adjustment and are necessarily less satisfactory than direct records from such large water-surfaces.

Direct evaporation-results are not usually obtainable on large water-surfaces as it is seldom practicable to measure the elements of inflow and outflow with sufficient accuracy to give the resulting difference closely enough to determine evaporation without a relatively large error. In many reservoirs evaporation may not be over 5 per cent of the water stored and close records of other items of supply are required if consistent results are to be secured.

There are some lakes, however, which have no inflow in some years or in parts of all years or which have only a few tributaries which are measurable. Fluctuation-records on such lakes enable evaporation to be measured directly. Such lakes have to have an impervious bed, and preferably not be subject to wide fluctuation in stage. With large fluctuations some bank-storage will occur on nearly all lakes which will affect monthly estimates of evaporation even if the return balances the storage over longer time-periods.

Records are available on several lakes which meet these requirements for direct evaporation-estimates. These have been assembled by the writer, as far as they have come to his attention, in the following discussion. While evaporation from closed lakes eventually results in increased salt-content of the lake-water none of the lakes discussed herein have a sufficiently high salt-content to affect the rate of evaporation. On Great Salt Lake the present salt-content is sufficiently high to result in a 25 to 30 per cent reduction in the rate of evaporation. Mono Lake has a sufficient salt-content to result in an evaporation-rate a little lower than that of fresh water. On both of these lakes the conditions of inflow do not permit sufficiently close measurement to enable their fluctuations to be used as a measure of evaporation.

In all cases the evaporation has been computed as the sum of the lowering of the lake plus rainfall plus depth of inflow. Where rainfall and inflow exceed evaporation the lake rises and the same computation is made with the rise of the lake given a negative sign.

Walker Lake

Walker Lake in western Nevada receives the surplus runoff of Walker River and other addi-

tional minor drainage-areas. Increased diversions from Walker River for irrigation have resulted in a generally downward trend for the Lake; its present stage is about 70 feet lower than the highest known stage of the last century. The present elevation of the Lake is about 4030 feet and its area is about 90 square miles.

Gage-height records are available from 1928 to 1932 and less frequently for 1933 and 1934. These records are obtained for the United States Geological Survey by the Navy Ammunition Depot at Hawthorne. Rainfall is measured at Schurz at the north end of the Lake. Inflow from Walker River is also measured at Schurz. There is some additional inflow from the locally tributary drainage-area. This is small, however, particularly in years of below average rainfall, such as those during the period of record.

The indicated annual evaporation for the six-year period is as given in Table 1.

Table 1

Year	Quantities in feet			
	Lowering of Lake-surface	Depth of inflow	Depth of rainfall	Total indicated depth of evaporation
1929	3.25	0.10	0.30	3.65
1930	3.50	0.10	0.65	4.25
1931	3.65	0.05	0.70	4.40
1932	3.20	0.65	0.35	4.20
1933	3.20	0.30	0.35	3.85
1934	3.80	0.15	0.55	4.50
Mean	3.45	0.20	0.50	4.15

Pyramid Lake

This Lake receives the surplus runoff of the Truckee River. Other inflow is negligible in amount. The runoff of Truckee River is largely diverted for irrigation and the Lake has been steadily lowering in recent years. Formerly, when at high stages, Pyramid Lake overflowed to Winnemucca Lake. The present area of the Lake is now about 200 square miles and its elevation about 3830 feet.

Gage-height records on the Lake are fragmentary prior to 1932. Annual evaporation can be computed since 1927. The gage-height record of Harry C. Dukes, Truckee River Water Master, has been used for Lake elevations. The Water Master's record of flow in Truckee River at Pyramid Dam since 1928 has been used as the inflow to the Lake. Flow past Derby Dam was similarly used for 1927; return flow below Derby Dam approximately balances the diversions. Rainfall at Nixon was used when available, Lahontan being used to fill missing periods in the Nixon record.

The annual results are as given in Table 2.

Table 2

Year	Quantities in feet			
	Lowering of Lake-surface	Depth of inflow	Depth of rainfall	Total indicated depth of evaporation
1927	1.2	2.7	0.2	4.1
1928	1.6	2.2	0.2	4.0
1929 } 1931	11.35	0.5	1.35	13.2
1932	2.45	0.95	0.35	3.75
1933	3.55	0.25	0.30	4.10
1934	3.15	0.15	0.65	3.95
Mean	2.9	0.85	0.40	4.15

Eagle Lake

Eagle Lake is a land-locked lake about 20 miles northwest of Susanville, California. It was formed by a lava-flow across the valley of Willow Creek. Springs arise in Willow Creek below

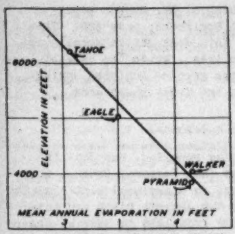

FIG. 1—RELATION OF MEAN ANNUAL EVAPORATION AND ELEVATION FOR LAKES IN WESTERN GREAT BASIN AREA

the Lake which had a flow of about 12,000 acre-feet per year when measured in 1904-05. These springs have been considered by some to be supplied from Eagle Lake; differences in quality of water and lack of variation of spring-flow with Lake stage make this open to doubt, however. The discharge of the springs, if it all came from Eagle Lake, would amount to about 0.03 foot in depth on the Lake per month at the Lake stages for the years of gage-height record.

Eagle Lake had an area of about 30,000 acres at its higher stages. Its present elevation is about 5100 feet. Gage-height records are available from 1915 to 1923, except during 1921, from observations made by those interested in tapping the Lake by tunnel as a source of water-supply. Since 1923 the tunnel has been in operation but its discharge has not been measured sufficiently closely to enable evaporation to be determined.

The nearest rainfall-record is at Susanville. Inflow which occurs through various local creeks has not been measured. Such streams cease to flow, usually in May, following the end of the rainy season and of melting of snow. There are no indications of springs within the Lake. Evaporation can be computed for the months without appreciable inflow. These include May in two years of small runoff and extend to December in some years of early rains. These records gave an average evaporation for the eight months from May to December, inclusive, of 2.75 feet. By comparison with the records on other lakes the evaporation for the remaining four months was estimated to be 0.75 foot, giving an annual evaporation of 3.50 feet.

Lake Tahoe

Direct estimates of evaporation from Lake Tahoe based on inflow, outflow, rainfall, and fluctuations cannot be made as the inflow occurs in several unmeasured streams. Pan-records of evaporation have been maintained since 1921 by the United States Weather Bureau, using the standard Weather Bureau pan. Some earlier, but less complete, records are also available. In volume 90, page 271, of the Transactions of the American Society of Civil Engineers, Ivan Houk gives the mean of the pan-records from 1916 to 1923 for all months except February.

In winter months the pan frequently freezes, although the Lake remains open. The missing winter months were estimated by comparison with records on other lakes. The results from the pan were multiplied by 0.9 to give evaporation from the surface of the Lake.

For the eight months from April to November, inclusive, the mean evaporation from the Lake obtained as explained is 2.59 feet. Based on the results given by Mr. Houk and comparison with other lakes the evaporation during the remaining four months is estimated to be 0.48 foot, giving a total mean annual evaporation of 3.07 feet.

Effect of elevation on evaporation

The preceding estimates of mean annual evaporation for Walker, Pyramid, Eagle, and Tahoe lakes are plotted in relation to their elevations in Figure 1. This shows a consistent relationship between evaporation and elevation. This particular relationship is representative only of the conditions of this area. It does not apply to the records given later for Tulare and Elsinore lakes in California in areas subject to different humidity- and temperature-conditions. For the western portion of the Great Basin Area evaporation appears to decrease about one foot per year for each increase of 2200 feet in elevation. This rate of variation if applied to high elevations leads to an indicated evaporation of zero at an elevation of 13,000 feet. As evaporation occurs at such high elevations the relationship shown in Figure 1 is evidently not applicable at elevations above 7000 or 8000 feet.

Tulare Lake

Tulare Lake is in the San Joaquin Valley of California at an elevation of 200 feet. It receives the unused portion of the runoff of several streams. Its area at higher stages exceeds 150,000 acres. The Lake has been dry in recent years.

Prior to 1918 the inflow to Tulare Lake was evaporated; since 1918 much of the inflow has been pumped for irrigation. The Lake bed is a tight clay and there is no seepage into or out of the Lake. The pumping from the Lake since 1918 has eliminated its use as a measure of evaporation but prior to that date the fluctuations during periods of no inflow represent evaporation.

The available records were included by the writer in a discussion of Mr. Houk's paper on evaporation in volume 90, Transactions of American Society of Civil Engineers, page 328. The resulting mean evaporation as there given was 4.60 feet per year. This does not materially exceed the evaporation for the lower lakes in the Western Great Basin Area. While the rate of evaporation from Tulare Lake is greater during the summer months, the greater humidity during the winter months more than offsets the lower winter temperature in the Great Basin Area.

Lake Elsinore

Lake Elsinore is in Southern California. It receives the surplus runoff of San Jacinto River. At times in the past it has both been dry and has overflowed into Temescal Creek. Locally tributary runoff around the Lake is negligible in amount except in occasional winter months of large inflow from the San Jacinto River. Stream-flow records on San Jacinto River and Lake gage-heights are available since 1916. The evaporation from the Lake from 1916 to 1922 as computed by the writer has been published in volume 90, page 329, Transactions of American Society of Civil Engineers. These computations have been continued through 1934. The mean for 1916 to 1922 was 4.5 feet per year; the addition of the last 12 years gives a mean of 4.55 feet for the 19-year period. During this period the evaporation in individual years varied from a minimum of 4.25 feet to a maximum of 4.8 feet, or a range from 93 to 105 per cent of the mean. Lake Elsinore has an elevation of about 1200 feet. Its evaporation is closely similar to that of Tulare Lake.

Monthly evaporation

The preceding discussion has related to the annual evaporation. In reservoirs subject to large fluctuations, the area exposed to evaporation varies during the year and it is essential to use the monthly rates of evaporation. The same method can be used to estimate the monthly loss as that discussed for the annual evaporation if gage-height records are obtained sufficiently frequently. The available records on the same lakes were used for this purpose as far as possible.

Results by months show more relative variations than those for years. This is to be expected. The gage-readings on the lakes were generally taken at about monthly intervals, but not always at the end of the month. Individual readings are subject to wind-action at the time of reading as only single gages were used. Inflow may be several times the evaporation in some months. Using the available records the results in Table 3 were obtained.

Table 3--Monthly evaporation from lakes of California and Nevada
(Based on records of inflow, rainfall, and lake-fluctuation, except for Lake Tahoe, which is based on evaporation-pan records)

Month	Walker Lake	Pyramid Lake	Eagle Lake	Lake Tahoe	Tulare Lake	Lake Elsinore
	ft	ft	ft	ft	ft	ft
January	0.20	0.25	0.15[a]	0.10[a]	0.12	0.12
February	0.15	0.25	0.15[a]	0.10[a]	0.13	0.11
March	0.20	0.30	0.20[a]	0.16[a]	0.25	0.22
April	0.20	0.30	0.25[a]	0.24	0.30	0.38
May	0.25	0.35	0.30	0.32	0.50	0.47
June	0.40	0.40	0.40	0.36	0.70	0.54
July	0.50	0.40	0.50	0.47	0.80	0.66
August	0.55	0.40	0.45	0.48	0.60	0.65
September	0.65	0.45	0.45	0.35	0.60	0.55
October	0.45	0.40	0.30	0.22	0.30	0.44
November	0.40	0.35	0.20	0.15	0.20	0.26
December	0.25	0.30	0.15	0.12[a]	0.10	0.16
Year	4.20	4.15	3.50	3.07	4.60	4.56

[a]Estimated--no direct record.

The results for Walker Lake are the means for four or five records for each month from 1928 to 1932. The results for Pyramid Lake are for the three years, 1932 to 1934; a number of inconsistencies appeared in the individual months and the results have been somewhat smoothed by adjusting a few months in relation to the adjacent ones. The monthly record for Pyramid Lake needs confirmation from additional years of observation.

As previously described, the records on Eagle Lake cover only the months without material inflow. The months of January to April, inclusive, have been estimated by comparison with the other lakes. The records for Lake Tahoe cover only April to November, and the evaporation from December to March was estimated. There are some scattered observations for these months which serve as a guide for their interpolation. The results for Tulare Lake are those previously given; those for Lake Elsinore are the means for the 19 years of record.

The monthly evaporation shows variations for the different lakes. No consistent relationship is shown between monthly evaporation and elevation such as was found for the annual evaporation. Walker Lake shows a larger amount of evaporation later in the summer than the other lakes. These records should furnish a basis for computing monthly evaporation-losses from storage for reservoirs within areas having similar conditions.

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DISCUSSION OF "EVAPORATION FROM LARGE WATER-SURFACES BASED ON RECORDS IN CALIFORNIA AND NEVADA"

Charles H. Lee

Attempts to use lakes and reservoirs as large-scale evaporating pans are frequently unsuccessful because of inability to accurately measure inflow and outflow. Mr. Harding is fortunate in being able to assemble annual data for as many as six lakes in relatively close proximity. It is to be noted, however, that at Lake Tahoe, the highest of these lakes, the data are from a pan-record. He states that the pan is a standard United States Weather Bureau pan, but reference to the source of publication shows that it is a submerged floating circular pan, 4 feet in diameter and 10 inches deep, submerged 7 inches and located 60 feet from the dam which partly shelters it from the wind.

The coefficient to be applied to the Tahoe record to reduce it to open-lake conditions may be open to question. Mr. Harding, in using 0.90, apparently adopts an average of coefficients applied to this record by Meeker, who used 0.92 (Trans. Amer. Soc. Civil Eng., v. 90, p. 296, 1927), and Follansbee, who used 0.88 (Trans. Amer. Soc. Civil Eng., v. 99, p. 711, 1934).

In his paper, however, Follansbee (p. 706) presents data comparing evaporation from a 3-foot square and a 4-foot diameter circular floating pan with that from open-lake surface, indicating that there is wide variation in the coefficient. The average value for nine comparisons which he presents is 0.83, with a spread of from 0.70 to 0.92 and no consistent difference in the coefficient for the two pans. There may be some question, therefore, as to the propriety of giving as much weight to the Tahoe pan-record in comparison with lake-records as is done by Mr. Harding on his Figure 1.

Mr. Harding points out that the relationship between evaporation and elevation below elevation of 7000 feet does not apply at higher elevations. This conclusion is confirmed by observations made by Frank Adams on the east slope of Mount Whitney, California, during the summer of 1905 for the Office of Experiment Stations, United States Department of Agriculture (see reference in Trans. Amer. Geophys. Union, 15th annual meeting, p. 368, 1934). Records of daily evaporation were observed at six stations ranging from 4500 to 14,500 feet in elevation. These indicated that between elevations of 7000 and 10,000 feet the rate of decrease of evaporation with elevation decreased; and that above 10,000 feet there was very little decrease of evaporation with elevation. Using a correction-factor of 0.90 for the Tahoe pan-record, and following the general shape of the graphical curve for Mount Whitney, the writer has modified the curve on Mr. Harding's Figure 1 as shown upon Figure 1. The modified curve is believed to show more correctly the relation of evaporation and elevation in the Great Basin Region than the straight-line relation shown by Mr. Harding. The latter is indicated upon Figure 1 by a dotted line.

Additional information regarding evaporation at high altitude in this region is furnished by a floating-pan record kept at Crooked Creek, Mono County, California, since 1920 by the Bureau of Water Works and Supply of the City of Los Angeles. The station is equipped with a standard United States Geological Survey floating pan 3 feet square and 18 inches deep, located on Owens River at the junction of Crooked Creek where the elevation is 6700 feet above sea-level. The average annual evaporation from 1920 to 1933, as furnished the writer through the courtesy of the Bureau, was 39 inches. Applying a coefficient of 0.83, as indicated by the data presented by Follansbee for this type of pan, the equivalent annual evaporation for open-lake surface is 2.70 feet. This value lies very close to the curve indicated upon Figure 1.

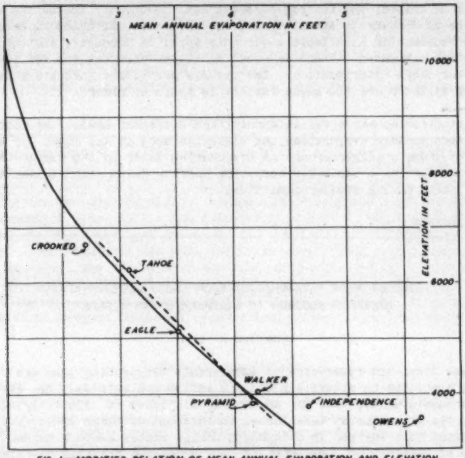

FIG. 1—MODIFIED RELATION OF MEAN ANNUAL EVAPORATION AND ELEVATION FOR LAKES IN WESTERN GREAT BASIN AREA

A floating-pan record similar to that at Crooked Creek was kept by the writer on Owens River east of Independence, Inyo County, California, for a three-year period from 1908 to 1911 (Trans. Amer. Soc. Civil Eng., v. 78, p. 148). The elevation of the pan was 3750 feet above sea-level. The average annual evaporation during the period of record was 67 inches. Applying a factor of 0.83, the equivalent annual evaporation for open-lake surface is 4.63 feet. This value lies slightly to the right of the curve on Figure 1, possibly indicating the influence of the warm desert-conditions from southeastern California, which do not affect climatic conditions in the Great Basin further north.

A lake-record in the Great Basin Region not mentioned by Mr. Harding is that at Owens Lake, Inyo County, California. This Lake has no outlet and is fed by Owens River and several small streams. During the nine-year period from 1906 to 1914, inclusive, there are available detailed data of inflow, lake-levels, and lake-area (Trans. Amer. Soc. Civil Eng., v. 90, pp. 332-333). The average area of exposed water-surface was 58,173 acres, and the average specific gravity of the lake-water was 1.11. The elevation of lake-surface was 3570 feet.

The writer was connected with the obtaining of these data and a number of years ago made a study of them to determine the rate of evaporation from the Lake. The observations also included a laboratory-study of the effect of varying specific gravity of the water of Owens Lake upon rate of evaporation. It was found that the average annual evaporation during the nine-year period, including rainfall, was 60.8 inches. Correcting this to obtain equivalent evaporation from a fresh-water lake-surface, a value of 5.62 feet was obtained. This lies considerably to the right of the curve on Figure 1. Owens Lake is more exposed to the warm desert-influence than is Independence. Furthermore, the Lake was relatively shallow compared with the lakes considered by Mr. Harding, the average depth being less than 10 feet. The latter condition probably facilitated warming of the water and thus intensified the evaporation-rate especially during the summer months.

Consideration of the records at Independence and Owens Lake tends to confirm Mr. Harding's conclusion that the relationship of evaporation and elevation indicated by Walker, Pyramid, Eagle, and Tahoe lakes is confined to the western Great Basin Region.

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BANK STORAGE-LOSS AND RECOVERY OF MISSOURI RIVER DISCHARGE DURING DROUGHT OF 1934

H. C. Beckman

Whenever measurements show that the discharge of a stream becomes smaller as it passes downstream to a considerably larger drainage-area and no diversions of water are known to exist between the places of measurement, curiosity is always aroused as to the cause, and a question may be raised as to the accuracy of the measurements purporting to show the decrease.

Small streams sometimes disappear in fault-planes and crevices in rocky regions with relatively high slopes, or in flat sand- and gravel-bars, and then reappear full-size farther downstream. This behavior, however, represents no decrease in the discharge but merely means that the stream is following an underground rather than a surface-course for that part of its travel.

A large stream flowing a long distance through a hot, dry region may lose more water through evaporation than it gains from small tributary inflow. Such a loss is permanent and is not recovered by the stream.

When the rainfall in the upper part of a drainage-basin is much greater than in the lower part, the peak discharge of the stream may be greater in the upper than in the lower part. This difference, however, does not indicate a loss of water between the two places. It merely means that the discharge at the lower point is spread over a longer period of time, which reduces the crest rate of flow but does not reduce the total volume.

During the severe drought of 1934 the discharge of the Missouri River as it flowed through North Dakota and South Dakota showed decreases that cannot be explained on any of the grounds mentioned above. These decreases, however, were merely temporary and were recovered a few months later.

The precipitation in North Dakota and South Dakota had been below normal during each of the years 1930 to 1933, the average during the 4-year period having been only 72 per cent of the normal in South Dakota and 87 per cent in North Dakota. The year 1934, therefore, began in those States with a large accumulated deficiency in precipitation. As a climax to this long dry period, the precipitation in both States during 1934 was the smallest within the 45-year period of records of the United States Weather Bureau.

Under these conditions the underground water-storage was unquestionably very low, as was indicated by the small discharge of the streams tributary to the Missouri River. The moderate rains that occurred produced practically no increase in the small flow of these tributaries.

The United States Geological Survey, in cooperation with the United States Corps of Engineers, maintains 19 gaging-stations to determine the daily discharge of the Missouri River at well-distributed places between the source of the River in southwestern Montana and its mouth near St. Louis, Missouri. The effect of the drought of 1934 (with the preceding accumulated deficiency in precipitation) upon the discharge of the Missouri River was most marked in the stretch between Bismarck, North Dakota, and Omaha, Nebraska. Although the drought extended above Bismarck, it was not so bad there as below, especially in South Dakota, and it did not produce in so large a degree the particular effect upon the flow of the River which it is desired to portray here. This effect was also not noticed in the more humid region below Omaha. For this reason, the present discussion will be limited to the stretch of the River between Bismarck and Omaha, a river-distance of 790 miles.

Under the cooperative program referred to above, gaging-stations were maintained throughout 1934 on the Missouri River at Bismarck and at Omaha, also one on each of the eight largest tributaries, including 63 per cent of the total tributary drainage-area between Bismarck and Omaha.

Table 1 shows the mean monthly data during the year ending September 30, 1934, for the following items:

(1) The measured discharge of the Missouri River at Bismarck.
(2) The discharge from the total tributary drainage-area between Bismarck and Omaha, computed on the assumption that the discharge from the unmeasured area was proportional to that from the measured area, which was 63 per cent of the total. This assumption, of course, does not give highly accurate results.
(3) The computed loss by evaporation from the Missouri River between Bismarck and Omaha, determined from the best experimental information available. The figures given are intended to be approximate only.

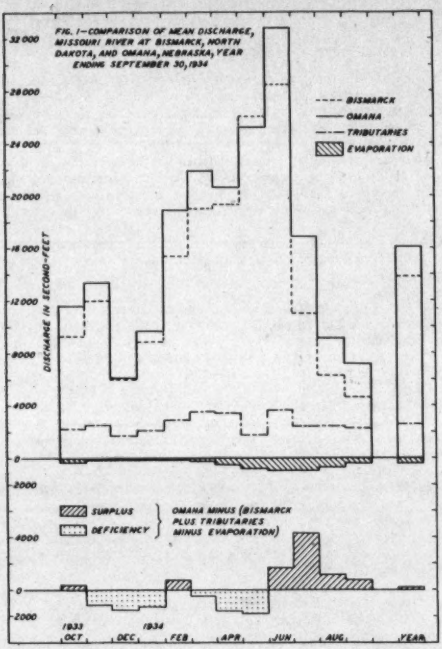

Table 1--Comparison of mean discharges of Missouri River System during drought of 1934

Month and year	Measured discharge at Bismarck	Total discharge tributaries	Computed evaporation loss	Measured discharge at Omaha[a]	Difference (4) − [(1) + (2) − (3)]	
					Monthly	Cumulative
	(1)	(2)	(3)	(4)	(5)	(6)
1933	sec-ft	sec-ft	sec-ft	sec-ft	sec-ft	sec-ft
October	9343	2220	300	11660	+ 397	+ 397
November	12050	2520	100	13350	-1120	- 723
December	5974	1770	100	6072	-1572	-2295
1934						
January	8877	2160	100	9706	-1231	-3526
February	15370	2930	100	18950	+ 750	-2776
March	19030	3520	200	21900	- 450	-3226
April	19260	3440	500	20610	-1590	-4816
May	26040	1730	800	25170	-1800	-6616
June	28450	3580	900	32810	+1680	-4936
July	11000	2400	900	16850	+4350	- 586
August	6249	2400	700	9073	+1124	+ 538
September	4561	2240	400	7165	+ 764	+1302
Year	13810	2560	420	16080	+ 110	.....

[a] For monthly periods ten days later than the calendar months shown.

(4) The measured discharge of the Missouri River at Omaha for monthly periods 10 days later than the calendar months shown. This time-shift was made to allow for the time of flow from Bismarck to Omaha at a medium-high stage. The tributary-discharge described under (2) was also shifted for time by a proportional amount.
(5) The discharge at Omaha less the algebraic sum of the discharge at Bismarck, the tributary inflow, and the loss by evaporation--that is, (4) - [(1) + (2) - (3)]. Where the figure for Omaha is greater than the algebraic sum of the others, the difference is indicated as a plus quantity, and where less it is indicated as a minus quantity.
(6) The cumulative totals of the differences obtained as explained under (5).

An examination of the graphs of Figure 1 and of the last two columns of Table 1 will show that there was a loss in discharge between Bismarck and Omaha during November, December, and January. This can be accounted for by the large amount of water stored as ice. During February a part of the ice melted, and there was a partial recovery in discharge. The ice went out during March, and the remainder of the water so stored was returned as discharge. This would naturally be expected to produce a gain in discharge sufficient to eliminate the previous cumulative deficiency. Table 1 and Figure 1, however, show a loss for March and also for April and May. These losses were not recovered until the period June to September.

The explanation here offered for the loss in discharge between Bismarck and Omaha during March to May and the later recovery during June to September relates to the special conditions that prevailed in that region as a result of the severe drought of 1934 culminating the deficient precipitation of the preceding four years, as described above. Under these conditions the underground-water storage must have been very low. The River also was low during October to January. From the first of February to the middle of June it rose intermittently a total amount of 3 feet at Bismarck, 8 feet at Omaha, and proportionally between these places. Under these conditions a large amount of water was stored in the previously dry banks of this 790-mile stretch of river, and the ground-water level throughout that region was appreciably raised. From the middle of June to the end of August the River again fell to the low stage of early February, and the water previously stored in the ground was returned to the stream and the accumulated loss in discharge was recovered.

Conditions were ideal for such loss and recovery in discharge during the time and in the region considered. The discharge-records obtained at gaging-stations on the Missouri River above Bismarck showed similar but smaller losses and recoveries, which can be explained by the fact that in that region the drought was not so severe. The records collected at stations in the more humid region below Omaha did not show loss and recovery. It is believed that during periods of normal precipitation they would not occur, or at least not to a marked extent, between Bismarck and Omaha.

So large a temporary loss of water from a large stream and its later recovery, in the absence of artificial regulation or control, is of unusual interest. Although similar conditions but with smaller losses may often be suspected, they are seldom so well established by adequate and reliable supporting records.

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Rolla, Missouri

THE USE OF THE BURT PHOTOTUBE IN AN INTEGRATING PYRHELIOMETER

N. W. Cummings

Introduction

The high voltage used with the phototube gives this apparatus an important advantage over the thermocouple or resistance-thermometer in any device employing vacuum-tubes and designed for automatically integrating or recording the total energy from the Sun and sky. Without vacuum-tubes, on the other hand, there seems to be no escape from at least three objections: (1) Its initial cost is high, and it requires a continuous outlay for paper or film; (2) its care requires a considerable amount of the time of a trained person; and (3) it is not suited for use on board ship. These objections apply in less degree to the instrument about to be described.

Although the current passed by a phototube is not strictly proportional to the intensity of the total energy of all wave-lengths received by the tube, nevertheless it has been found possible to formulate a simple function which expresses the relation between energy and quantity of

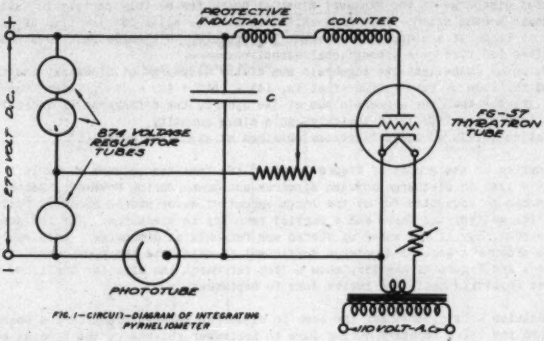

FIG. 1—CIRCUIT—DIAGRAM OF INTEGRATING PYRHELIOMETER

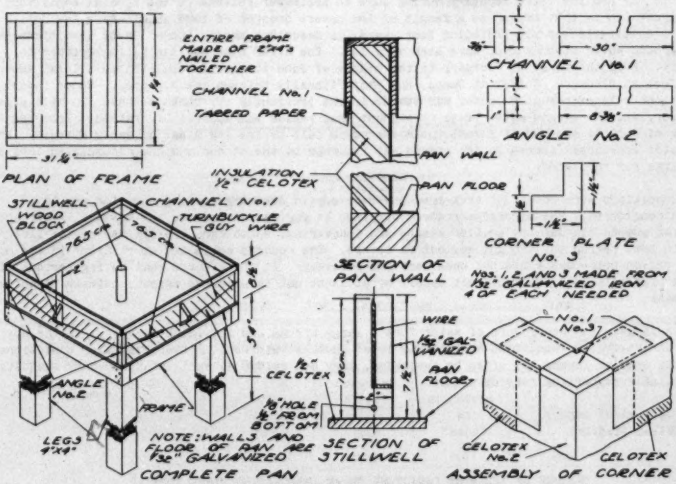

FIG. 2—DETAILS OF INSULATED EVAPORATING PAN

electricity with fair consistency. The physical explanation for this seems to be based on the fact that a large part of the energy received from the Sun is in the visible wave-lengths to which the tube responds.

Description of apparatus

The circuit, shown in Figure 1, is a modification of the one commonly used for obtaining the linear timing axis of a cathode-ray oscillograph. Current from a power supply of 270 volts passes through the tube to a 28-microfarad condenser, C. When the condenser-voltage has reached a certain predetermined value which is approximately 180 volts, it discharges through the thyratron. In doing this it operates a six-dial Veeder-Root counter wound for 24 volts. The 4-henry protective inductance prevents excessive accelerations in the counter-mechanism.

The circuit illustrated in Figure 1 causes the thyratron to fire consistently at a voltage

very close to the mean value. This fact is easily ascertained by employing a constant-current tube such as the Westinghouse RJ 571 to replace the phototube. The current can then be measured and the frequency of the pulses counted. A Weston portable galvanometer was used with a shunt for determining the current, and the deviation from constancy of firing was found to be less than the error in reading the galvanometer at about half-scale deflection. There seems to be no doubt that the tube always fires within two per cent of the same voltage, and consequently the counter integrates the total quantity of electricity passing through the phototube.

The pan, shown in Figure 2, is a modification of the one described by Cummings and Richardson (Phys. Rev., v. 30, pp. 527-534, 1927). The free water-surface is 76.5 cm on a side giving an area which can be taken as numerically equal to 10L where L is the latent heat. Likewise, the top of the peg in the stilling well is at such a height above the bottom of the tank as to make $S = 10\ \Delta T$, where S is the heat storage in calories per square centimeter of open water-surface and ΔT is the change in body-temperature in degrees F.

This area of water-surface is nearly twice as great as that previously employed, and therefore permits the use of a thinner layer of insulation without undue heat-leakage through the walls. A half-inch layer of celotex seems to be satisfactory. This has the advantage of a smaller storage of heat in the insulating material.

Experimental procedure and computations

The pan and counter were each read at frequent intervals on each of 17 days. It was the intention to comply with a schedule of hourly readings extending from sunrise to sunset, but since the routine part of the work was done by Federal Emergency Relief Administration students, it was not always possible to carry out this plan perfectly. On a few days the observations were continued for half a day only.

The readings of the pan were used for computing the resultant radiation in calories per square centimeter per hour received on a horizontal surface. These computations were made according to the equation

$$H = I - B - LE\,(1 + R) + S + C \qquad (1)$$

where H is the resultant radiation, I is the insolation, B is the back-radiation to the sky, both in calories per square centimeter, LE is the latent heat of the water evaporated per square centmeter, R is Bowen's ratio, S is the heat-storage per square centimeter, and C is the leakage per square centimeter of open water-surface. All the terms in equation (1) are integrated over the same basic time-interval with the hour as the time-unit.

These resultant radiations were all reduced to the values they would have had if the water-surface temperature had been 80° F and if the sky-conditions had remained constant. For this purpose, the excess of the surface-temperature over 80° F was multiplied by the appropriate entry in Table 1 and the result added algebraically to H as computed from equation (1). This entry is

Table 1--Correction for difference in back-radiation

Temperature °F	dB/dT	Temperature °F	dB/dT	Temperature °F	dB/dT	Temperature °F	dB/dT
32	0.222	50	0.248	68	0.274	86	0.303
33	0.223	51	0.249	69	0.276	87	0.305
34	0.224	52	0.250	70	0.278	88	0.306
35	0.226	53	0.252	71	0.279	89	0.308
36	0.228	54	0.253	72	0.281	90	0.310
37	0.229	55	0.255	73	0.282	91	0.312
38	0.230	56	0.256	74	0.284	92	0.313
39	0.232	57	0.258	75	0.286	93	0.315
40	0.233	58	0.260	76	0.287	94	0.317
41	0.234	59	0.261	77	0.289	95	0.318
42	0.236	60	0.262	78	0.290	96	0.320
43	0.238	61	0.264	79	0.292	97	0.321
44	0.239	62	0.265	80	0.293	98	0.323
45	0.241	63	0.267	81	0.295	99	0.325
46	0.242	64	0.268	82	0.296	100	0.326
47	0.243	65	0.270	83	0.298	101	0.328
48	0.245	66	0.272	84	0.300	102	0.330
49	0.246	67	0.273	85	0.302	103	0.332

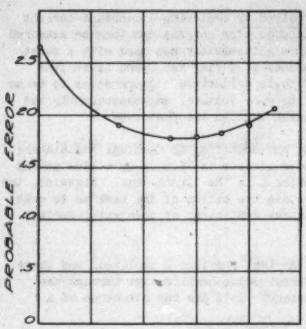

FIG. 3

the one corresponding to the average of the actual surface-temperature and 80° F. Table 1 is based on Stefan's law.

Corrections were made for the thermal expansion of the water by multiplying the entry in Table 2 by ΔT and adding algebraically to LE before multiplying by (1 + R). The tabular value used in this case is the one corresponding to the body-temperature.

Certain graphical computations based on the values of H as corrected for back-radiation and thermal expansion indicated that the leakage-coefficient was about 0.68 calory per hour per square centimeter of free water-surface for every degree of temperature-difference between the dry bulb and the water-body. Accordingly, the values of H were further corrected for leakage on this assumption. The coefficients k and r in the equation

$$h = (c - kt)/r \qquad (2)$$

were then found by the method of least squares, regarding h as having the same dimensions as H, c as the counter reading, t as the time in hours from the beginning of a run (preferably sunrise), and k and r as empirical constants. The probable error was then found and the whole procedure repeated with other leakage-coefficients as shown in Figure 3.

Results and conclusions

The coefficient giving the smallest probable error was estimated from Figure 3 to be 0.5 and the constants were once more determined. The final values are k = 56.3 and r = 4.28. The corresponding probable error is 1.8 calories per hour. This is about five per cent of the average insolation. A computation of the leakage-coefficient based on the rated conductivity of the insulating material yielded 0.32. The assumed conductivity was 0.30 BTU per hour per degree F per square foot per inch thick.

Table 2--Correction for expansion of water

Temperature	Expansion	Temperature	Expansion
°F	cal/°F	°F	cal/°F
39	0.00	63	1.03
40	0.05	64	1.07
41	0.11	65	1.10
42	0.16	66	1.14
43	0.20	67	1.17
44	0.25	68	1.21
45	0.29	69	1.24
46	0.34	70	1.27
47	0.38	71	1.31
48	0.43	72	1.34
49	0.47	73	1.37
50	0.51	74	1.41
51	0.56	75	1.44
52	0.60	76	1.47
53	0.64	77	1.51
54	0.68	78	1.54
55	0.73	79	1.57
56	0.77	80	1.60
57	0.81	81	1.63
58	0.84	82	1.66
59	0.88	83	1.69
60	0.92	84	1.72
61	0.96	85	1.75
62	1.00	86	1.78

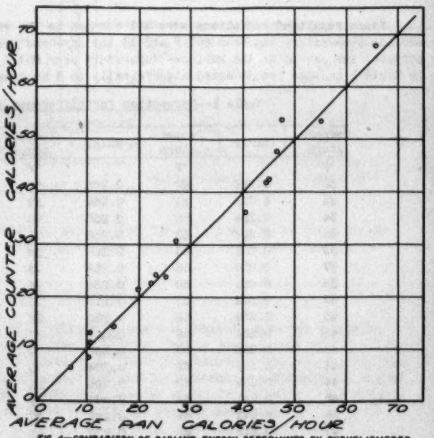

FIG. 4—COMPARISON OF RADIANT ENERGY DETERMINED BY PYRHELIOMETER AND BY EVAPORATING PAN

The discrepancy (0.5-0.32) may probably be accounted for by the liberal coating of white paint that was put on the insulating material to protect it from the weather and to reflect as much direct radiation as possible. The paint doubtless permeated into the material so as to increase its conductivity. Moreover, in spite of the white paint, the outer surfaces of the slabs receiving direct solar radiation must have been kept at a temperature somewhat higher than the dry bulb. Since the prevailing direction of heat-leakage was into the water, this increase of temperature of the surface of the insulating material must have had the effect of an apparent increase in conductivity.

Figure 4 shows the relation between h as computed from the phototube-pyrheliometer readings and H as obtained from the pan.

It is not surprising that equation (2) yields fairly consistent results when we remember that in the morning and evening the light entering the window of the phototube comes chiefly from the sky and is therefore richer in short waves than it is during the middle part of the day. Toward the ends of the day there are, accordingly, pulses which are not accompanied by much heat. The kt-term subtracts these out.

The errors shown by Figure 4 are due to several causes, but perhaps one of the most serious is the warping of the walls of the pan due to temperature-changes. If some means can be found for measuring nocturnal back-radiation, the seriousness of this difficulty can be eliminated by making a continuous run of several days' duration. The total algebraic result of warping would then be negligible. Arrangements are being undertaken for carrying out this plan.

The writer desires to express appreciation to Dr. White of the Physics Department of the University of California for his suggestion of covering the thyratron with a hood in order to help minimize erratic behavior due to temperature-changes. Thanks are also extended to Dr. Nicholas Ricciardi, President of the San Bernardino Valley Junior College and to Dean Frank B. Lindsay for assigning Federal Emergency Relief Administration students to this work, as well as to the students themselves. Most of the observations were made by Newell Call and William Hand, but Guy Harris and Robert Whaling also helped. Hayden Gordon, technician of the College, assisted in various ways. Mr. Moore and Mr. Watson of the Smithsonian Institution at Table Mountain rendered valuable aid in some preliminary investigations.

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THE RELATION BETWEEN THE LOWERING OF THE PIEZOMETRIC SURFACE AND THE RATE AND DURATION OF DISCHARGE OF A WELL USING GROUND-WATER STORAGE

Charles V. Theis

When a well is pumped or otherwise discharged, water-levels in its neighborhood are lowered. Unless this lowering occurs instantaneously it represents a loss of storage, either by the unwatering of a portion of the previously saturated sediments if the aquifer is nonartesian or by release of stored water by the compaction of the aquifer due to the lowered pressure if the aquifer is artesian. The mathematical theory of ground-water hydraulics has been based, apparently entirely, on a postulate that equilibrium has been attained and therefore that water-levels are no longer falling. In a great number of hydrologic problems, involving a well or pumping district near or in which water-levels are falling, the current theory is therefore not strictly applicable. This paper investigates in part the nature and consequences of a mathematical theory that considers the motion of ground-water before equilibrium is reached and, as a consequence, involves time as a variable.

To the extent that Darcy's law governs the motion of ground-water under natural conditions and under the artificial conditions set up by pumping, an analogy exists between the hydrologic conditions in an aquifer and the thermal conditions in a similar thermal system. Darcy's law is analogous to the law of the flow of heat by conduction, hydraulic pressure being analogous to temperature, pressure-gradient to thermal gradient, permeability to thermal conductivity, and specific yield to specific heat. Therefore, the mathematical theory of heat-conduction developed by Fourier and subsequent writers is largely applicable to hydraulic theory. This analogy has been recognized, at least since the work of Slichter, but apparently no attempt has been made to introduce the function of time into the mathematics of ground-water hydrology. Among the many problems in heat-conduction analogous to those in ground-water hydraulics are those concerning sources and sinks, sources being analogous to recharging wells and sinks to ordinary discharging wells.

C. I. Lubin, of the University of Cincinnati, has with great kindness prepared for me the following derivation of the equation expressing changes in temperature due to the type of source or sink that is analogous to a recharging or discharging well under certain ideal conditions, to be discussed below.

The equation given by H. S. Carslaw (Introduction to the mathematical theory of the conduction of heat in solids, 2nd ed., p. 152, 1921) for the temperature at any point in an infinite plane with initial temperature zero at any time due to an "instantaneous line-source coinciding with the axis of z of strength Q" (involving two-dimensional flow of heat) is

$$v = (Q/4\pi\kappa t)\, e^{-(x^2 + y^2)/4\kappa t} \qquad (1)$$

where v = change in temperature at the point x,y at the time t; Q = the strength of the source or sink--in other words, the amount of heat added or taken out instantaneously divided by the specific heat per unit-volume; κ = Kelvin's coefficient of diffusivity, which is equal to the coefficient of conductivity divided by the specific heat per unit-volume; and t = time.

The effect of a continuous source or sink of constant strength is derived from equation (1) as follows: Let $Q = \varphi(t')dt'$; then $v_{(x,y,t)} = \int_0^t [\varphi(t')/4\pi\kappa(t-t')]\, e^{-(x^2+y^2)/4\kappa(t-t')}\, dt'$. Let $\varphi(t') = \lambda$, a constant; then $v_{(t)} = (\lambda/4\pi\kappa)\int_0^t [e^{-(x^2+y^2)/4\kappa(t-t')}/(t-t')]\, dt'$. Let $u = (x^2+y^2)/4\kappa(t-t')$; then

$$v_{(t)} = (\lambda/4\pi\kappa)\int_{(x^2+y^2)/4\kappa t}^{\infty} [e^{-u}/(t-t')]\, [(x^2+y^2)/4\kappa]\, [du/u^2]$$

$$= (\lambda/4\pi\kappa)\int_{(x^2+y^2)/4\kappa t}^{\infty} (e^{-u}/u)du \qquad (2)$$

The definite integral, $\int_{(x^2+y^2)/4\kappa t}^{\infty} (e^{-u}/u)du$, is a form of the exponential integral, tables of which are available (Smithsonian Physical Tables, 8th rev. ed., table 32, 1933; the values to be used are those given for Ei (-x), with the sign changed). The value of the integral is given by the series

$$\int_x^{\infty} (e^{-u}/u)du = -0.577216 - \log_e x + x - x^2/2 \cdot 2! + x^3/3 \cdot 3! - x^4/4 \cdot 4! + \ldots\ldots (3)$$

Equation (2) can be immediately adapted to ground-water hydraulics to express the draw-down at any point at any time due to pumping a well. The coefficient of diffusivity, , is analogous to the coefficient of transmissibility of the aquifer divided by the specific yield. (The term "coefficient of transmissibility" is here used to denote the product of Meinzer's coefficient of permeability and the thickness of the saturated portion of the aquifer; it quantitatively describes the ability of the aquifer to transmit water. Meinzer's coefficient of permeability denotes a characteristic of the material; the coefficient of transmissibility denotes the analogous characteristic of the aquifer as a whole.) The continuous strength of the sink is analogous to the pumping rate divided by the specific yield. Making these substitutions, we have

$$v = (F/4\pi\tau)\int_{r^2 s/4\tau}^{\infty} (e^{-u}/u)du \qquad (4)$$

in which the symbols have the meanings given with equation (5). In equation (4) the same units must of course be used throughout. Equation (4) may be adapted to units commonly used

$$v = (114.6F/\tau)\int_{1.87r^2 s/\tau t}^{\infty} (e^{-u}/u)du \qquad (5)$$

where v = the draw-down, in feet, at any point in the vicinity of a well pumped at a uniform rate; F = the discharge of the well, in gallons a minute; τ = the coefficient of transmissibility of aquifer, in gallons a day, through each 1-foot strip extending the height of the aquifer, under a unit-gradient--this is the average coefficient of permeability (Meinzer) multiplied by the thickness of the aquifer; r = the distance from pumped well to point of observation, in feet; s = the specific yield, as a decimal fraction; and t = the time the well has been pumped, in days.

Equation (5) gives the draw-down at any point around a well being pumped uniformly (and continuously) from a homogeneous aquifer of constant thickness and infinite areal extent at any time. The introduction of the function, time, is the unique and valuable feature of the equation. Equation (5) reduces to Thiem's or Slichter's equation for artesian conditions when the time of pumping is large.

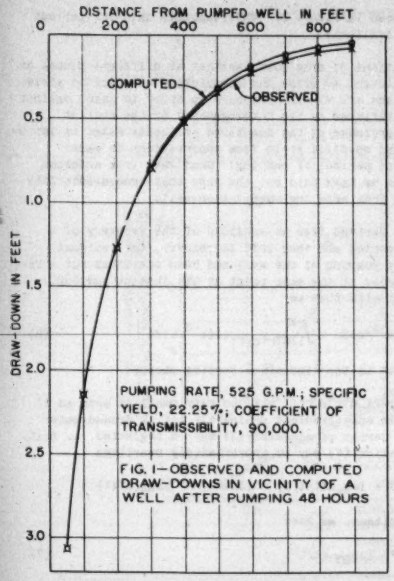

FIG. 1—OBSERVED AND COMPUTED DRAW-DOWNS IN VICINITY OF A WELL AFTER PUMPING 48 HOURS

Empirical tests of the equation are best made with the data obtained by L. K. Wenzel (Recent investigations of Thiem's method for determining permeability of water-bearing sediments, Trans. Amer. Geophys. Union, 13th annual meeting, pp. 313-317, 1932; also Specific yield determined from a Thiem's pumping test, Trans. Amer. Geophys. Union, 14th annual meeting, pp. 475-477, 1933) from pumping tests in the Platte Valley in Nebraska. Figure 1 presents the comparison of the computed and observed draw-downs after two days of pumping. The observed values are those of the generalized depression of the water-table as previously determined by Mr. Wenzel. The computed values are obtained by equation (5), using values of permeability and specific yield that are within one per cent of those determined by Mr. Wenzel by other methods. The agreement represented may be regarded as showing either that the draw-downs have been computed from known values of transmissibility and specific yield or that these factors have been computed from the known draw-downs.

Theoretically, the equation applies rigidly only to water-bodies (1) which are contained in entirely homogeneous sediments, (2) which have infinite areal extent, (3) in which the well penetrates the entire thickness of the water-body, (4) in which the coefficient of transmissibility is constant at all times and in all places, (5) in which the pumped well has an infinitesimal diameter, and (6) - applicable only to unconfined water-bodies - in which the water in the volume of sediments through which the water-table has fallen is discharged instantaneously with the fall of the water-table.

These theoretical restrictions have varying degrees of importance in practice. The effect of heterogeneity in the aquifer can hardly be foretold. The effect of boundaries can be considered by more elaborate analyses, once they are located. The effect of the well failing to penetrate the entire aquifer is apparently negligible in many cases. The pumped well used in the set-up that yielded the data for Figure 1 penetrated only 30 feet into a 90-foot aquifer. The coefficient of transmissibility must decrease during the process of pumping under water-table conditions, because of the diminution in the cross-section of the area of flow due to the fall of the water-table; however, it appears from Figure 1 that if the water-table falls through a distance equal only to a small percentage of the total thickness of the aquifer the errors are not large enough to be observed. In artesian aquifers the coefficient of transmissibility probably decreases because of the compaction of the aquifer, but data on this point are lacking. The error due to the finite diameter of the well is apparently always insignificant.

In heat-conduction a specific amount of heat is lost concomitantly and instantaneously with fall in temperature. It appears probable, analogously, that in elastic artesian aquifers a specific amount of water is discharged instantaneously from storage as the pressure falls. In nonartesian aquifers, however, the water from the sediments through which the water-table has fallen drains comparatively slowly. This time-lag in the discharge of the water made available from storage is neglected in the mathematical treatment here given. Hence an error is always present in the equation when it is applied to water-table conditions. However, inasmuch as the rate of fall of the water-table decreases progressively after a short initial period, it seems probable that as pumping continues the rate of drainage of the sediments tends to catch up with the rate of fall of the water-table, and hence that the error in the equation becomes progressively smaller.

For instance, although the draw-downs computed for a 24-hour period of pumping in Mr. Wenzel's test showed a definite lack of agreement with the observations, similar computations for a

48-hour period gave the excellent agreement shown in Figure 1. Unfortunately data for periods of pumping longer than 48 hours have not been available.

The equation implies that any two observations of draw-down, whether at different places or at the same place at different times, are sufficient to allow the computation of specific yield and transmissibility. However, more observations are always necessary in order to guard against the possibility that the computations will be vitiated by the heterogeneity of the aquifer. Moreover, it appears that the time-lag in the drainage of the unwatered sediments makes it impossible at present to compute transmissibility and specific yield from observations on water-levels in only one observation-well during short periods of pumping. Good data from artesian wells have not been available, but such data as we have hold out the hope that transmissibility and specific yield may be determined from data from only one observation-well.

A useful corollary to equation (5) may be derived from an analysis of the recovery of a pumped well. If a well is pumped for a known period and then left to recover, the residual draw-down at any instant will be the same as if pumping of the well had been continued but a recharge well with the same flow had been introduced at the same point at the instant pumping stopped. The residual draw-down at any instant will then be

$$v' = (114.6F/\tau) \left[\int_{1.87r^2s/\tau t}^{\infty} (e^{-u}/u)du - \int_{1.87r^2s/\tau t'}^{\infty} (e^{-u}/u)du \right. \qquad (6)$$

where t is the time since pumping started and t' is the time since pumping stopped.

In and very close to the well the quantity $(1.87r^2s/\tau t')$ will be very small as soon as t' ceases to be small, because r is very small. In many problems ordinarily met in ground-water hydraulics, all but the first two terms of the series of equation (3) may be neglected, so that, if $Z = (1.87r^2s/\tau t)$ and $Z' = (1.87r^2s/\tau t')$ equation (6) may be approximately rewritten

$$v' = (114.6F/\tau) \left[-0.577 - \log_e Z + 0.577 + \log_e Z(t/t')\right] = (114.6F/\tau) \log_e(t/t')$$

Transposing and converting to common logarithms, we have

$$\tau = (264F/v') \log_{10} (t/t') \qquad (7)$$

This equation permits the computation of the coefficient of transmissibility of an aquifer from an observation of the rate of recovery of a pumped well.

Figure 2 shows a plot of observed recovery-curves. The ordinates are log (t/t'); the abscissas are the distances the water-table lies below its equilibrium-position. According to equation (7) the points should fall on a straight line passing through the origin. Curve A is a plot of the recovery of a well within 3 feet of the well pumped for Mr. Wenzel's test, previously mentioned. Most of the points lie on a straight line, but the line passes below the origin. This discrepancy is probably due to the fact that the water-table rises faster than the surrounding pores are filled. The coefficient of permeability computed from the equation is about 1200, against a probably correct figure of 1000. Curve B is plotted from data obtained from an artesian well near Salt Lake City. The points all fall according to theory.

Curve C shows the recovery of a well penetrating only the upper part of a nonartesian aquifer of comparatively low transmissibility. It departs markedly from a straight line. This curve probably follows equation (6), but it does not follow equation (7), for in this case $(1.87r^2s/\tau t')$ is not small. Equation (6), involving r and s, neither of which may be known in practice, is not of practical value for the present purpose. Further empirical tests may show that it is feasible to project the curve to the origin, in the neighborhood of which $(1.87r^2s/\tau t')$ becomes small, owing to the increase in t and t', and apply equation (7) to the extrapolated values so obtained in order to determine at least an approximate value of the transmissibility.

The paramount value of equation (5) apparently lies in the fact that it gives part of the theoretical background for predicting the future effects of a given pumping regimen upon the water-levels in a district that is primarily dependent on ground-water storage. Such districts may include many of those tapping extensive nonartesian bodies of ground-water. Figure 3 shows the vertical rate of fall of the water-level in an infinite aquifer, the water being all taken from storage. The curves are plotted for certain definite values of pumping rate, transmissibility, and specific yield, but by changing the scales either curve could be made applicable to any values set up.

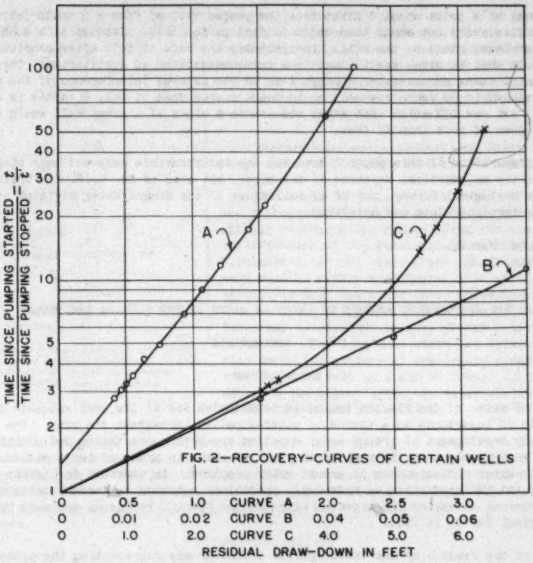

FIG. 2—RECOVERY-CURVES OF CERTAIN WELLS

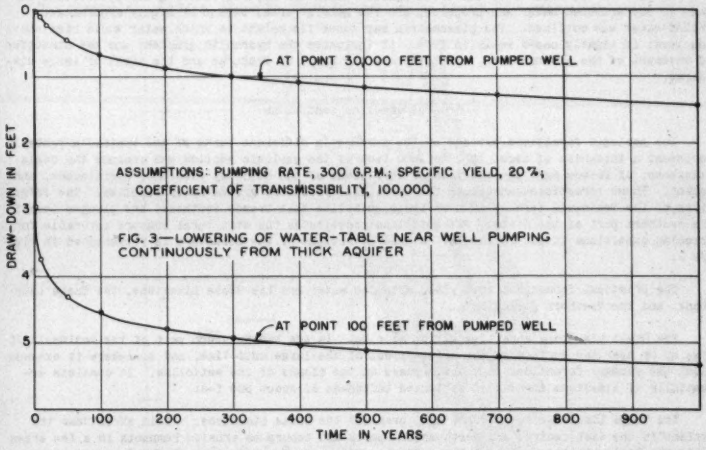

FIG. 3—LOWERING OF WATER-TABLE NEAR WELL PUMPING CONTINUOUSLY FROM THICK AQUIFER

These theoretical curves agree qualitatively with the facts generally observed when a well is pumped. The water-level close to the well at first falls very rapidly, but the rate of fall soon slackens. In the particular case considered in Figure 3 the water-level at a point 100 feet from the pumped well would fall during the first year of pumping more than half the distance it would fall in 1000 years. A delayed effect of the pumping is shown at distant points.

the water-level at a point about 6 miles from the pumped well of Figure 3 would fall only minutely for about five years but would then begin to fall perceptibly, although at a much less rate than the water-level close to the well. Incidentally the rate of fall after considerable pumping is so small that it might easily lead to a false assumption of equilibrium. The danger in a pumping district using ground-water storage lies in the delayed interference of the wells. For instance, although in 50 years one well would cause a draw-down of only 6 inches in another well 6 miles away, yet the 100 wells that might lie within 6 miles of a given well would cause in it a total draw-down of more than 50 feet.

In the preparation of this paper I have had the indispensable help not only of Dr. Lubin, who furnished the mathematical keystone of the paper, but also of Dr. C. E. Van Orstrand, of the United States Geological Survey, and of my colleagues of the Ground Water Division of the Survey, who cordially furnished data and criticism.

U. S. Geological Survey,
Washington, D. C.

THE PIEZOMETRIC SURFACE OF ARTESIAN WATER IN THE FLORIDA PENINSULA

V. T. Stringfield

Introduction

The ground-water of the Florida Peninsula constitutes one of its most valuable natural resources and is of importance as a source of water-supplies throughout the area. The problems relating to the development of ground-water supplies are both quantitative and qualitative. They include such problems as the decline in yield of wells in areas of large withdrawals of water and salt-water contamination of ground-water supplies. In order to facilitate a better understanding and interpretation of hydrologic conditions relating to these local ground-water problems, a general survey of the artesian water in the Florida Peninsula was made by the United States Geological Survey in 1934.

As part of the results of the investigation a contour-map representing the piezometric surface of the artesian water was prepared, and the general areal extent of highly mineralized ground-water was outlined. The piezometric map shows the height to which water would rise above sea-level in tightly cased wells in 1934. It indicates the hydraulic gradient and the direction of movement of the ground-water, and therefore the areas of recharge and the areas of large discharge.

General artesian conditions

The geologic formations exposed at the surface in different parts of the Peninsula probably represent a thickness of about 1000 to 1500 feet of the geologic section and include the Ocala limestone, of Eocene age, and the younger formations of the Miocene, Pliocene, Pleistocene, and Recent. These formations constitute the rocks that yield the ground-water supplies. The formations of the Peninsula form an arch or broad anticline that trends southeast and plunges toward the southern part of the State. The anticline constitutes the structural feature favorable for artesian conditions in the Peninsula. A general outline of the structure is represented in Figure 1.

The principal formations that yield artesian water are the Ocala Limestone, the Tampa Limestone, and the Hawthorn Formation.

The Ocala Limestone underlies all of Florida. In the northwestern part of the Peninsula it lies at or near the surface on the eroded crest of the large anticline, and elsewhere it extends under the younger formations that are exposed on the flanks of the anticline. It consists essentially of limestone and has an estimated thickness of about 500 feet.

The Tampa Limestone, of Miocene age, overlies the Ocala Limestone. It is at or near the surface in the west-central and northwestern parts and occurs as erosion remnants in a few areas where the Ocala Limestone is near the surface. Well-records indicate that the formation is absent in the eastern and northeastern part of the Peninsula. The Formation consists essentially of limestone and has an estimated thickness of about 200 feet.

The Hawthorn Formation, of Miocene age, overlies the Tampa Limestone or in some places rests

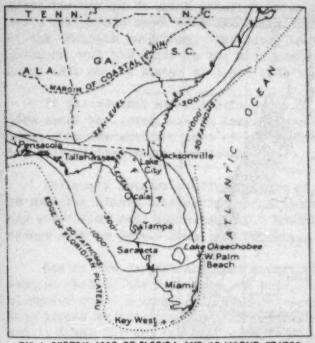

FIG. 1—SKETCH-MAP OF FLORIDA AND ADJACENT STATES REPRESENTING GENERAL GEOLOGIC STRUCTURE BY CONTOURS ON TOP OF THE EOCENE FORMATIONS (FROM STATE GEOLOGIC MAP OF FLORIDA)

directly on the Ocala Limestone. It is generally overlain by younger material, which in the southern part of the Peninsula attains considerable thickness. The Hawthorn is present throughout the Peninsula except where the Ocala and Tampa limestones are at or near the surface. It consists of about 500 feet of interbedded marl, limestone, and clay.

The artesian wells penetrating these formations range in depth from less than 100 to about 1000 feet.

The areas in which flowing wells can be obtained are represented in Figure 2. They include an area that extends several miles inland along the east coast, the southern part of the Peninsula, the valleys of the Kissimmee River and Peace Creek, and a belt along the west coast. Within the general area of flow there are relatively high districts in which wells will not flow. Also in parts of the Peninsula shown as nonflowing areas, flows may be obtained in some of the relatively low districts. The height to which the artesian water will rise above the surface of the ground ranges from a fraction of a foot to about 50 feet. In nonflowing wells in the higher areas the water may stand as much as 100 feet below the surface.

The height to which the artesian water will rise above sea-level ranges from a few feet in some areas on or near the coast to 120 feet in the central part of the Peninsula. Fluctuations of head range from less than a foot to several feet. Some of the causes of these fluctuations are: (1) Withdrawal of water from wells either by natural flow or pumpage; (2) fluctuations in rainfall; (3) discharge of water into drainage-wells; (4) ocean-tides; (5) fluctuations in barometric pressure.

Piezometric surface

The piezometric surface, shown by means of contours on Figure 3, a generalized map, repre-

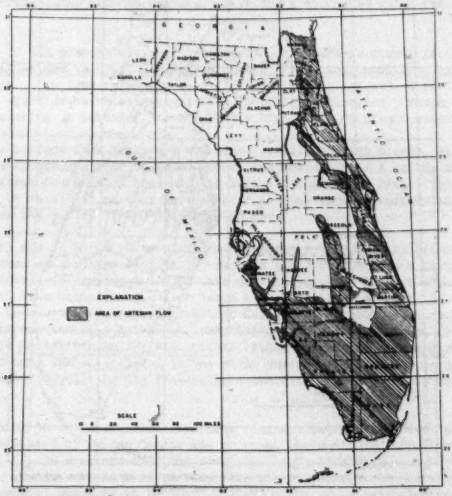

FIG. 2—MAP OF FLORIDA PENINSULA REPRESENTING THE AREA OF ARTESIAN FLOW

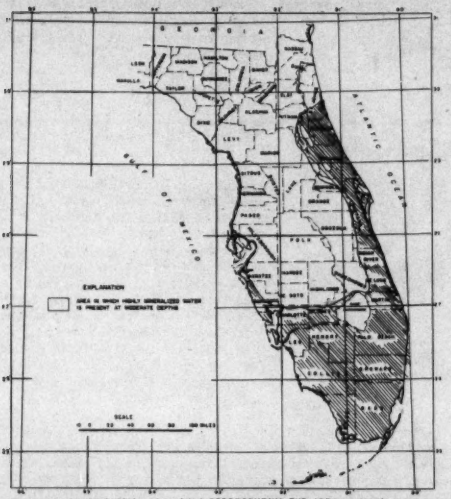

FIG. 4—MAP OF FLORIDA PENINSULA REPRESENTING THE AREA IN WHICH HIGHLY MINERALIZED GROUND-WATER IS PRESENT AT RELATIVELY MODERATE DEPTHS

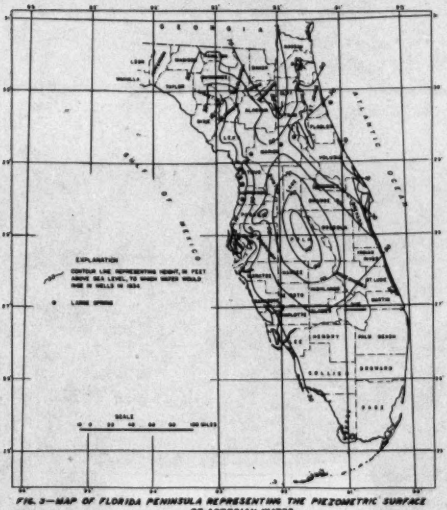

FIG. 3—MAP OF FLORIDA PENINSULA REPRESENTING THE PIEZOMETRIC SURFACE OF ARTESIAN WATER

sents the height to which artesian water would rise above mean sea-level in 1934 in tightly-cased wells that yield water from the Ocala or Tampa limestones or in some localities the lower part of the Hawthorn Formation. The water in these beds is in general under approximately the same pressure, but the water in the middle and upper parts of the Hawthorn Formation has pressure-heads that may be higher or lower than those in the underlying rocks.

In the central and northern parts of the Peninsula the piezometric surface is 90 feet or more above sea-level, but in the intervening saddle it is only about 40 to 50 feet above sea-level. In the southern part of the Peninsula it is relatively flat and stands from a few feet to about 50 feet above sea-level.

Obviously because of fluctuations of the pressure-head the shape of the piezometric surface is changing almost constantly, and a representation of it at any time shows the conditions at any other time only approximately. Nevertheless, it shows the major features, which presumably change only in detail from time to time.

One of the largest and most conspicuous features of the piezometric surface is seen in the central part of the Peninsula, in Polk and adjacent counties, where it has the shape of an elongated dome, a large part of which is 90 to 120 feet above sea-level. The surface of this dome slopes to the Atlantic Coast on the east, where it has an altitude of about 30 to 50 feet, and to Tampa Bay and the Gulf of Mexico on the west, where it has an altitude of 10 to 20 feet. On the northwest it is separated by a saddle from another dome-shaped surface in Pasco County. The total east-west extent of the large central dome is about 120 miles. It slopes northward to an altitude of about 50 feet in Marion County and southward into Glades County, where the piezometric surface becomes relatively level at an altitude of about 50 feet. The total north-south extent is about 150 miles. The shape of the peizometric surface indicates local recharge of the water-bearing formations in the central part of the Peninsula and lateral movement of the water in all directions therefrom.

The Ocala and Tampa limestones are overlain in part of this recharge-area by relatively impervious members of the Hawthorn Formation. However, well-records indicate that in parts of the area the Hawthorn Formation is relatively thin or absent, and unconsolidated sands rest directly on the water-bearing formations. Also within the area there are numerous lakes that probably occupy old sink-holes now filled with sands that permit downward percolation of water. The altitude of the ground-surface is relatively high. Few surface-streams are present, and the rainfall drains into the numerous lakes and depressions, providing a source of water for recharge of the formations.

The small dome of the piezometric surface in northeastern Pasco County is in an area where the Tampa or Ocala Limestone is near the surface of the ground and conditions are favorable for ground-water recharge. The less permeable Hawthorn Formation is present in part of this area, but within the area there are sink-holes and lakes occupying sink-holes through which recharge may take place, accounting in part for the relatively high level of ground-water.

The piezometric surface from Tampa and vicinity, in Hillsborough County, northeastward along the valley of the Hillsborough River to Pasco County has the shape of a valley that heads in the saddle between the Pasco County high area and the larger central high area. This valley in the piezometric surface is caused in part by ground-water leakage through springs and outcrops of the Tampa Limestone along the valley of the Hillsborough River.

In Citrus County and adjacent parts of Hernando and Levy counties the piezometric surface slopes from an altitude of about 40 feet in the eastern part to less than 5 feet in the western part, on the Gulf Coast. The ground-water in this area is supplied in part from the adjacent counties to the east. The Ocala Limestone or Tampa Limestone is at or near the surface, and sink-holes are well developed, especially in Citrus County, permitting local recharge. The Ocala Limestone is porous and even cavernous, permitting fairly free movement of the water. Most of this water appears as springs on the west coast. Along the Withlacoochee River in the northern part of Citrus County the water-level in the River during normal stages is approximately the same as the ground-water level. During flood-stages the River may contribute water to the water-bearing formations.

A second high area in the piezometric surface, rising about 50 to 90 feet above sea-level, is in the northwestern part of Putnam County and adjacent parts of Clay, Bradford, and Alachua counties. On the north, in Bradford and Clay counties, it forms a ridge about 70 or 80 feet above sea-level and extends at that altitude into Georgia. It slopes to the Atlantic Ocean on the east to an altitude of about 20 to 50 feet. On the south it is separated from the large

central high area by a broad saddle in Marion County, where the surface is about 40 to 50 feet above sea-level. On the west it extends into a broad area in Alachua County about 40 to 50 feet above sea-level, and also slopes to the Suwannee River Valley, where the piezometric surface ranges from a few feet to about 50 feet above sea-level.

In this area the artesian formations are not exposed where the piezometric surface has an altitude of 70 to 90 feet, but the typical sink-hole topography affords conditions favorable for recharge. In the southern and southwestern parts of the area recharge takes place through sink-holes or through the formations exposed at the surface. In the northern part of the area, although the piezometric surface is as much as 70 feet above sea-level, no recharge of the Ocala Limestone takes place locally, but water is supplied through a recharge-area in Georgia.

In Jacksonville and vicinity, in Duval County, there is a local depression in the piezometric surface about 6 miles in diameter and 30 feet deep. The lowest point of the depression is about 30 feet above sea-level and is in the vicinity of Water Works Park, in Jacksonville. This depression is caused in part by draft from wells in the vicinity.

In the saddle in Marion County the Ocala Limestone is at or near the surface and sink-holes are well developed, affording favorable conditions for recharge. The fact that the piezometric surface is low in spite of large recharge is to be explained in part by the discharge from Silver Springs and Blue Springs, two of the largest springs in the State, which have a combined maximum flow (discharge-measurements made by D. S. Wallace, District Engineer, U. S. Geol. Survey) of about 2000 second-feet.

One of the most extensive low areas of the piezometric surface is in Volusia and Flagler counties, where it is about 10 to 20 feet above sea-level. This low-pressure area is caused in part by the discharge of ground-water through springs in the valley of the St. Johns River and submarine discharge through springs and outcrops in the Atlantic Ocean. One of these springs is about 2-1/2 miles offshore east of Crescent Beach, St. Johns County.

Extending from the southeastern part of Putnam County into the northwestern part of Volusia County, between the valley of the St. Johns River and Crescent Lake, is a long ridge of the piezometric surface from 20 to 30 feet above sea-level. Sink-holes and lakes occupying sink-holes are present in this area, affording opportunity for ground-water recharge, which accounts in part for the ridge. A similar ridge is present in the southwestern part of Volusia County east of the St. Johns River Valley, but the contour-interval of the map (Fig. 3) is too large to represent it.

The piezometric surface forms a valley along the Suwannee River, and the ground-water level in the bottom of the valley generally is approximately the same as the water-level in the River. Along this valley the piezometric surface slopes from about 50 to 60 feet above sea-level near the Georgia line to less than 10 feet above sea-level on the Gulf of Mexico. During low stages of the Suwannee River its flow is derived largely from ground-water. During flood-stages of the River it loses water to the formations. Similar conditions are present along the lower course of the Santa Fe River, a tributary of the Suwannee.

In the southern part of Florida the piezometric surface ranges from a few feet to about 50 feet above sea-level. The artesian formations are deeply buried in this area, and no recharge takes place locally. Fresh water enters the formations in the high area in the central part of the Peninsula. The low hydraulic gradient indicates slight movement of ground-water toward the south. It appears fairly certain that the water-bearing formations have submarine outcrops only a few miles off the coast in the Atlantic Ocean. However, the low hydraulic gradient, together with the relatively high pressure of the ground-water, suggests that little water discharges through the submarine outcrops.

General relation of the piezometric surface to the areas of highly mineralized water

Records of deep wells indicate that salt water underlies the entire Peninsula. However, it is confined to rocks of great depth except in certain coastal areas and in the southern part of the State. The area in which highly mineralized water is present at moderate depths is shown in Figure 4.

In the central part of the Peninsula, where the pressure-head is high, the salt water occurs only at relatively great depths, but in the coastal areas, where the pressure is low, salt water is reached at shallow or moderate depths. This general relation is also found locally, as in

Volusia County, where water of relatively low mineral-content occurs in a high area of the piezometric surface, whereas highly mineralized water occurs in adjacent areas of low pressure-head. Other factors, such as the circulation of the ground-water, have an important part in controlling the distribution of the highly mineralized ground-water.

U. S. Geological Survey,
Washington, D. C.

PRELIMINARY REPORT ON PERIODOGRAM-ANALYSIS OF THE RAINFALL-RECORDS OF THE PACIFIC COAST OF NORTH AMERICA

Dinsmore Alter

It must be understood in the following that when the reality of rainfall-cycles is mentioned it does not in any way refer to the possibility of economic use of them.

In 1922 I established for many sections of the world the existence of a cycle which varied in length to keep step with changing sunspot-phase, and which completed its variation exactly nine times during one spot-cycle. This cycle was found very strongly in data from the Pacific Coast, dominated by stations from Southern California.

Two years ago Ervin Prouse in his master's thesis showed by means of a correlation-periodogram, in data mainly from the coastal stations of Oregon, the existence of a cycle which is exactly one-eighth of the sunspot-cycle, and of a second cycle which is exactly twelve of the shorter ones. This work of Mr. Prouse's is not yet published.

Two years ago I published in proceedings of the National Academy a new form of periodogram, fully as powerful as the correlation-periodogram and requiring only a small fraction of the time to compute. This periodogram has been improved since then. Essentially it expresses for each trial-lag the mean area per pair of data in the histogram.

The rapidity of calculation by the new method made feasible a much more pretentious undertaking than was possible before. Federal grants for student aid have made it possible to start this work. When completed the Pacific Coast of North America will have been analyzed in all regions where there are long rainfall-records. At present, work has been started on southwestern Alaska, Western Washington, Western Oregon, Northern California, and Southern California. As soon as the periodograms for these sections have been completed the Coast of Canada, Central California, and the Canal Zone will be undertaken, with any additional sections for which long records may be found.

Two of these sections, Western Washington and Northern California, have been carried far enough that definite results have been secured. In preparing the periodograms as computed for a section it is necessary to form running averages of each five consecutive points to prevent confusion because of the short-period terms.

The resulting periodogram of Western Washington shows very definitely a fundamental cycle of length 73 months. Furthermore, the minor peaks included within this interval are reproduced in each half of the periodogram with remarkable fidelity. There seems to me no question of the physical existence of this cycle. It must be noted also that the length of 73 months cannot be shifted as much as a month either way without spoiling the symmetry of the pattern. I must admit surprise in such a cycle. In all my previous work the short cycles which have been found were undoubtedly related to the sunspot-cycle. There is no question but that this cycle is more than half the length of the spot-cycle.

In Northern California a somewhat different situation occurs. Instead of completing a cycle in 73 months it is noted that the mean trend of the periodogram, so far as computed at present, is downward. This downward slope is far too great to be accidental and cannot be explained on any other basis than as a cycle with fundamental length more than 11 years. This periodogram will be continued and, when the length of the cycle has been determined, will be carried through at least two cycle-lengths.

In an early part of this investigation it was found that the ordinary method of eliminating the annual term is not sufficient for stations where its range is extreme, as it is on the Pacific Coast. After the ordinary elimination it becomes necessary to reduce each of the twelve months at each station used to a common standard deviation. Failure to do this undoubtedly is the cause

of apparent periodicities of length between 11 and 13 months, which have been found commonly in data. This will be illustrated in the complete report by a periodogram computed for data from Northern California for which this additional correction was not made.

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